IMPLICATIONS OF CLIMATE CHANGE ON CROP WATER REQUIREMENTS IN SAUDI ARABIA

BY

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DEDICATION

To all my family, who offered me unconditional love and support all the way since the beginning of my study

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All praise and thanks are due to my Lord, ALLAH SUBHAN WA TAALA, for giving me the health, knowledge and patience to complete this work. My sincere gratitude goes to my advisor Dr. Shakhawat Hossain Chowdhury who guided me with his dedicated attention, expertise and knowledge throughout this research. I am also grateful to my Committee Members Dr. Muhammad Abdallah Al-Zahrani and Dr. Muhammad Shariq Vohra for their constructive guidance and support. Thanks are also due to the Chairman of the Department of Civil and Environmental Engineering Dr. Nedal T. Ratrout, secretary for providing aid and to other staff members who helped me directly or indirectly. Special thanks are due to my colleagues in the Civil and Environmental Engineering Department, for their aid and support. Thanks are also due to all my friends for their support and encouragement.

My heartfelt gratitude is for my beloved father, mother, my wife and my kids as well as my brothers and sisters who always support me with their love, patience, encouragement and prayers. I would like to thank all members of my family for their moral support throughout my study.

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LIST OF ABBREVIATIONS

AEZ	Agro-Ecological Zones Modeling Framework
BCM	Billion Cubic Meters
BLS	Basic Linked System
CWR	Crop Water Requirement
ET_c	Actual Evapotranspiration
ET_o	Reference Evapotranspiration
FAO	Food and Agriculture Organization
GCM	General Circulation Model
GDP	Gross Domestic Product
IPCC	Intergovernmental Panel on Climate Change
K_c	Crop Growth Stage Coefficient
MAW	Ministry of Agriculture and Water of Saudi Arabia
MCM	Million Cubic Meter
Mha	Million Hectares

MOA	The Ministry of Agriculture of Saudi Arabia
MOEP	The Ministry of Economy and Planning of Saudi Arabia
MT	Million Tons
P_{eff}	Effective Rainfall
S1	Scenario 1: CWR at Current State of Temperature and Rainfall
S2	Scenario 2: CWR at Changed Temperature in 2050 and Current Rainfall
S3	Scenario 3: CWR at Changed Rainfall in 2050 and Current Temperature
S4	Scenario 4: CWR at Changed Temperature and Changed Rainfall in 2050
SGS	Saudi Geological Survey
SSYB	Saudi Statistical Year Book
TWW	Treated Wastewater

THESIS ABSTRACT

FULL NAME: **ABDULLAH ABDO AHMED ABBAS**

THESIS TITLE: IMPLICATIONS OF CLIMATE CHANGE ON CROP WATER REQUIREMENTS IN SAUDI ARABIA

MAJOR FIELD: CIVIL AND ENVIRONMENTAL ENGINEERING – WATER RESOURCES AND ENVIRONMENT

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This study investigated possible implications of climate change on crop water requirement (CWR) from 2011 to 2050 in Saudi Arabia. Four scenarios: (i) CWR at current state of temperature and rainfall (S1); (ii) CWR at the changed temperature in 2050 and current state of rainfall (S2); (iii) CWR at changed rainfall in 2050 and current state of temperature (S3); and (iv) CWR at changed temperature and changed rainfall in 2050 (S4), were investigated. The CROPWAT software from the Food and Agriculture Organization (FAO) was used to predict CWR. Assuming no change in the regulations relating to agriculture and irrigation in future, CWR was predicted to be 8713 – 9221 million cubic meters per year (MCM/yr) for the S1 - S4 scenarios. The overall increase in CWR was estimated to be in the range of 463 - 508 MCM/yr from 2011 to 2050, representing 5.3 – 6% increase for the same level of crop productions. Assuming linear increase from 2011 to 2050, increase in CWR was estimated to be in the range of 11.9 – 13 MCM/yr in each year from 2011. This increase was due to the increase in temperature mainly, while the effect of rainfall changes was minimal. Increase in CWR is equivalent to producing 4886 - 5360 tons of wheat per year. Sensitivity analysis was performed by shifting the growing periods for the main crops. Possible water conservation by shifting crop growing periods was estimated to be 732 – 904 MCM/yr. This study might be useful in explaining the negative effects of climate change on CWR in the arid regions and better planning for water resources management.

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KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS

DHAHRAN, SAUDI ARABIA

ملخص الرســــــــــالة

الاســــــم الكـامل: عبـدالله عبده احمـد عبـاس

عنـــوان الرســـــــــــالة: آثـــــــــار تغيــر المنـــــــاخ علـــى الاحتيــــاجـــــــات المـــــــائية للمحـــاصيل في المملكة العربية السعودية

التخصــص: هندسة مدنية ـ الموارد المــــــــائية والبيئية

تاريــــــــخ الدرجة العلمية: نوفمبر ، 2013 م

أجريت هذه الدراسة لأكتشاف التأثيرات المحتملة للتغيرات المناخية على الأحتياجات المائية للمحاصيل من عام 2011 – 2050 في المملكة العربية السعودية. وقد تم دراسة أربعة سيناريوهات مختلفة وهي : (1) الأحتياجات المائية للمحاصيل عند الوضع الحالي لدرجة الحرارة والأمطار. (2) الأحتياجات المائية للمحاصيل عند تغير درجة الحرارة في عام 2050 و الوضع الحالي للأمطار. (3) الأحتياجات المائية للمحاصيل عند تغيرالأمطار في عام 2050 و الوضع الحالي لدرجة الحرارة. (4) الأحتياجات المائية للمحاصيل عند تغير درجة الحرارة والأمطار في عام 2050. وقد تم استخدام برنامج (CROPWAT) الذي صمم بواسطة منظمة الأغذية والزراعة فاو (FAO) لغرض تخمين الأحتياجات المائية للمحاصيل. على إفتراض عدم وجود تغيير في اللوائح المتعلقة بالزراعة والري في المستقبل ، تم تخمين الاحتياجات المائية للمحاصيل بحوالي 8713 – 9221 مليون متر مكعب في السنه للأربعة سيناريوهات (S1 – S4). وتقدر الزيادة الكلية في الأحتياجات المائية للمحاصيل بحوالي 463 – 508 مليون متر مكعب في السنة من 2011 - 2050 والتي تمثل حوالي 5.3 – 6% لنفس المستوى من الانتاج المحصولي. بفرض ان هناك ازدياد خطي في الاحتياجات المائية للمحاصيل من 2011 – 2050 ، فأن الزيادة السنوية المقدرة تكون بين 11.9 – 13 مليون متر مكعب في السنة اعتباراً من 2011. والسبب في هذه الزيادة يرجع الى الزيادة في درجة الحرارة بشكل رئيسي ، في حين أن تأثير تغيرات هطول الأمطار كان ضئيلاً للغاية. بلغت الزيادة في الأحتياجات المائية بما يعادل انتاج 4886 – 5360 طن من القمح سنوياً. تم إجراء تحليل الحساسية أيضاً عن طريق تحويل فترات النمو للمحاصيل الرئيسية. من المحتمل ان يكون مجموع المياه المتوقع المحافظة عليها حوالي 732 – 904

مليون متر مكعب. من المتوقع ان تكون هذه الدراسة مفيده في شرح الأثار السلبية لتغير المناخ على الأحتياجات المائية للمحاصيل في المناطق القاحلة كما انها قد تسهم في التخطيط الأفضل لإدارة الموارد المائية في المملكة العربية السعودية.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران، المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

1.1 General

Global warming is one of the major problems in the recent decades [1]. It might have changed various climatic parameters, including temperature, precipitation, humidity, solar radiation, wind speed and soil moisture in the past decades. The atmospheric temperature has been widely used as an indicator of climatic change [2]. Climate change can have negative impacts on water resources, water supplies for domestic and industrial uses, irrigation and in stream ecosystems. Any change in the frequency and intensity of precipitation can affect the runoff, floods and droughts [3]. Climate change can also affect agricultural productions by extending the crop growing seasons, which may put agricultural activities at risk. Wide ranges of effects including increased water demands and reduced water availability have been reported from temperature increase [4]. Due to these impacts, crop water requirement (CWR) can be increased, which can bring a challenge to the countries with limited water reserves [4-5]. Being a country with limited freshwater resources, Saudi Arabia can have significant implications on CWR from climate change. For better management of the available resources and agricultural productions, it is important to understand the CWR, current level of water supplies and possible effects of climate change in future. This chapter presents the details of the study area in the following section.

1.2 Study Area

The Kingdom of Saudi Arabia is located in the arid region within latitude: 16.5ºN – 32.5ºN and longitude: 33.75ºE - 56.25ºE, surrounded by the Red Sea in the west; the Arabian Gulf and the United Arab Emirates in the east; Oman and Yemen in the south; and Jordan, Iraq and Kuwait on the north (Figure 1.1) [6-7].

The climate of Saudi Arabia is arid, typically described by cold and slightly wet winter with hot and dry summer [8]. Since the largest part of the country experiences different climate conditions during summer and winter, the climatic parameters are changed from place to place, even in the same region. The maximum monthly average temperature during the summer and winter months are in the ranges of 30 - 44°C and 15 - 28°C respectively, while the minimum monthly average temperature varies in the ranges of 16 - 28°C and 3 - 22°C during the summer and winter respectively. The temperature often exceeds 45°C in July in the central and Eastern regions (e.g. Riyadh, Qaseem, Al-Hassa, Hafr Al-Baten, etc.), while the highlands remain colder with the maximum temperature not exceeding 30°C (e.g. Asser, Al-Baha). The relative humidity is very low in most parts of the country, especially in the summer. In the coastal regions, it is approximately 30% or more in any season, while it can be as low as 10% in some other regions in July. The average annual rainfall in the country is approximately 123 mm, which varies from 49 mm/yr in the Madinah region to approximately 265 mm/yr in the southern part of the country [9-10, 13].

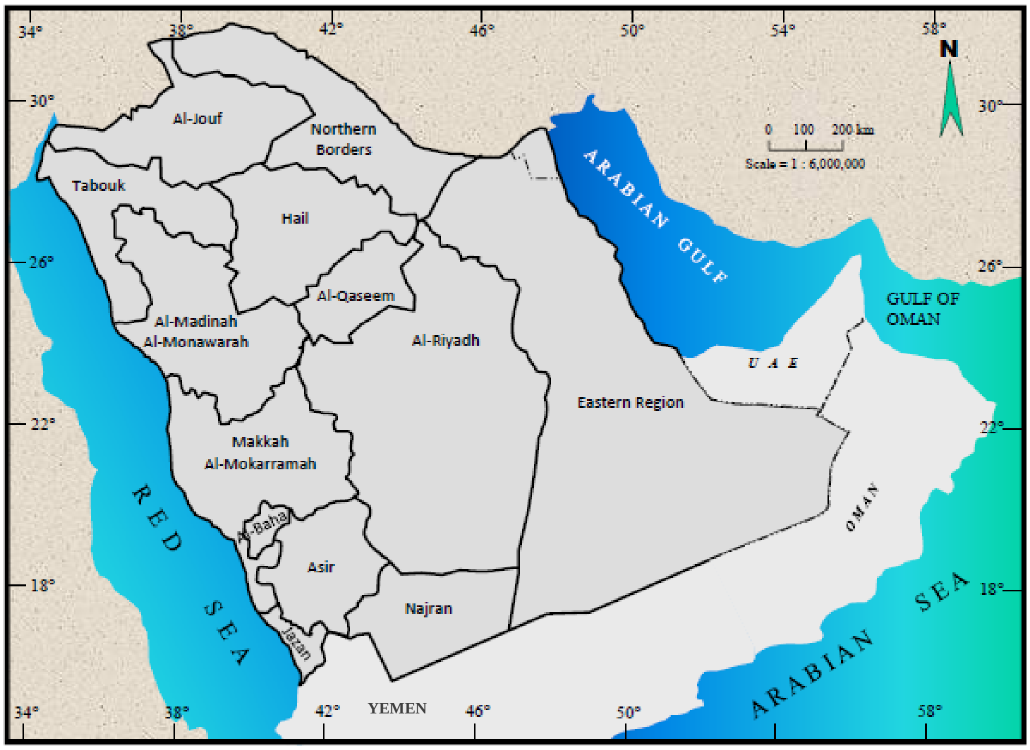

Figure 1.1: Location map of the Kingdom of Saudi Arabia [7]

The country has an area of about 2 million square kilometers (Km^2), which is divided into thirteen administrative regions [6, 10]. These are: Riyadh, Makkah, Madinah, Qaseem, Eastern region, Aseer, Tabouk, Hail, Northern region, Jazan, Najran, Al-Baha and Al-Jouf (Figure 1.1). The regions have variable areas of cultivated lands producing different types of crops [10-11]. This study uses the data on the cultivated lands and crop productions from the Saudi Statistical Yearbook (SSYB) and the Ministry of Agriculture (MOA) [10-11]. The most important agricultural crops in these regions are wheat, maize, millet, sorghum, barley, vegetables, clover, dates, grapes and citrus fruits [9-13]. However, these regions have different characteristics depending on topography, location and climatic features, which can have significant effects on the crop productions, water supply and CWR for each crop [6, 12]. The detail on the climatic conditions for each region is summarized in the following paragraphs.

Riyadh is the capital of Saudi Arabia, located in the central part of the Kingdom [6, 9]. The area and population are approximately 380 thousand km^2 and 6.8 million, equivalent to 19.5 and 25% of total area and population of the Kingdom respectively [6]. It is the largest region in the Kingdom in terms of cultivated area [10, 13]. The total cultivated area is about 182 thousand hectares; while the area for producing clover is highest (e.g., approximately 28% of the total cultivated lands), followed by dates (24%), vegetables (23%) and wheat (17%) respectively [10-11]. The most important agricultural areas in this region are: Al-Kharj, Al- Quwai'iah, Al- Diriyah, Al- Dawadmi and Al-Aflaj [6]. The average relative humidity varies between 15 and 51%, while the average temperature varies in the range of 8 - 43°C. The average annual rainfall is approximately 101 mm/yr, while the annual evapotranspiration ranges from about 1168 to 3979 mm/yr.

The average wind speed and sunshine period vary in the ranges of 6.5 - 13.9 km/hr and 6.3 - 9.6 hr [9].

Makkah region has an area and population of approximately 137 thousand km² and 6.9 million, equivalent to 7 and 25.5% of total area and population of the Kingdom respectively [6]. The major crops produced in the region are: dates, vegetables, sorghum, millet, maize, wheat, barley, fruits and clover [11]. The total cultivated area is approximately 33 thousand hectares, while the area for producing dates is highest (e.g., approximately 32% of the total cultivated lands), followed by vegetables (27%) and sorghum (17.5%) [10-11]. The most important areas in the region are: Jeddah, Taif, Laith and Qunfudah [6]. Makkah has an arid climate with warm winter and hot summer seasons [13]. The average temperature ranges from 19 to 38°C in winter and summer seasons. It has an average relative humidity ranging between 61 and 69%. The average wind speed and sunshine period vary in the ranges of 9 - 18 km/hr and 6.2 - 9.8 hr respectively. The annual rainfall is limited to about 59 mm/yr, while the annual evapotranspiration ranges from 1628 to 2763 mm/yr [9].

Madinah is located in the northwest of Makkah. The area and population are approximately 150 thousand km² and 1.7 million, equivalent to 7.7 and 6.6% of total area and population of the Kingdom respectively [6]. The cultivated area is about 27 thousand hectares, in which dates are produced in the largest fraction of cultivated land (e.g., approximately 58% of the total cultivated lands), followed by grapes (11%) and clover (9%). The cultivated areas for other crops (e.g. wheat, millet and maize) are not significant [10-11]. The climate of the region is a hot desert climate [13]. The average temperature ranges between 12 and 42°C. The humidity varies between 14% in summer and 43% in winter season. While the average annual evapotranspiration varies in the range of approximately 1259 - 3500 mm/yr, the annual rainfall is very low (approximately 49 mm/yr). The average wind speed and sunshine period vary in the ranges of 7.4 - 13 km/hr and 5.4 - 10.3 hr respectively [9].

Qaseem region has an area of about 73 thousand km² and population of 1.2 million, equivalent to 3.7 and 4.5% of total area and population of the Kingdom respectively [6]. Qaseem has the second largest cultivated area in the Kingdom, cultivating approximately 97 thousand hectares of agricultural lands. The major fractions of lands were cultivated for dates (40%), wheat (23%) and clover (15%). The climate of Qaseem is a typical hot desert climate with cold winter [13]. The average temperature varies in the range of 7 - 41°C during the winter and summer periods. The relative humidity varies between 13% in summer and 52% in winter season. The average wind speed and sunshine period vary in the ranges of 7.2 - 12.6 km/hr and 5.4 - 10.3 hr respectively. The rainfall is approximately 183 mm/yr, while the average annual evapotranspiration is in the range of 1037 - 3508 mm/yr [9].

Eastern region is located in the east of the country. The area and population are approximately 540 thousand km² and 4.1 million, equivalent to 27.6 and 15.1% of total area and population of the Kingdom respectively. The most important areas are: Al-Hasa, Hafr Al-Batin, Dammam, Jubail, etc. [6]. The total cultivated land is approximately 55 thousand hectares [10-11]. Eastern region is the sixth largest cultivated region in the Kingdom [10]. Wheat is produced in approximately 56% of the agricultural lands, followed by dates (25%), vegetables (10%) and clover (8%) respectively. The climate of Eastern region is typically hot and dry summer with cold rainy winter. The average temperature varies in the range of 9.2 - 41.2°C. The average relative humidity is between 32% in summer and 65% in winter season. The average annual rainfall is about 166 mm/yr, while the annual evapotranspiration ranges from 803 to 3174 mm/yr. The average wind speed and sunshine period vary in the ranges of about 6.8 - 10 km/hr and 6 - 9.2 hr respectively [9].

Aseer is located in the southwest part of the Kingdom. It has the population of about 1.9 million, equivalent to 7% of total population of the Kingdom [6]. It has the highest elevated highlands in the Arabian Peninsula reaching to approximately 3015 m in altitude near Abha. These characteristics give this region capability to make terraced farmland in the sloping terrains. In addition, there are several dams and reservoirs in valleys, which have been used for irrigation [13]. The total cultivated area is about 16 thousand hectares, while the largest area is for dates (31%) and wheat (19%) respectively [10-11]. The lowest average relative humidity in summer is about 30%, while it increases to 82% in winter. The temperature is relatively low (range: 8 - 31°C). However, it is distinguished by the highest rates of rainfall. The average annual rainfall is approximately 265 mm/yr with an average annual evapotranspiration ranges between approximately 1102 and 2413 mm/yr. The average wind speed varies in the range of 7.2 - 18 km/hr, while the sunshine period is in the range of 6.4 - 9% [9].

Tabouk region is located in the north west of the Kingdom, bounded by Al-Jouf, Hail, Madinah and the Red Sea. The total area and population in Tabouk are about 136 thousand km^2 and 791 thousands, which correspond to 6.9 and 2.9% of the total area and population in the Kingdom respectively [6]. The total cultivated area is about 36 thousand hectares, in which wheat occupies the largest cultivated area (49%), followed by clover

(25%) and dates (6%) respectively [10-11]. The climate in Tabouk is characterized by a desert climate, which is hot and dry in the summer and cold and rainy in winter [13]. The average maximum temperature is about 38°C in summer, whereas the average minimum temperature is below 3°C in winter. The average annual rainfall is approximately 58 mm/yr. The average relative humidity varies in the range of 21 - 50% during the dry and wet seasons. The wind speed changes between 7.2 and 12.6 km/hr. The average sunshine period ranges between 4.8 and 10.2 hours, whereas the average annual evapotranspiration varies in the range of 898 - 3124 mm/yr [9].

Hail region is surrounded by the regions of Qaseem, Madinah, Tabouk, Al-Jouf and northern border. The area of this region is about 120 thousand km², equivalent to 6.1% of the total area of the Kingdom, while the population is approximately 597 thousand (2.2%) [6]. There are various kinds of geographical terrain in this region, such as mountains, landscapes, valleys, sandy deserts and free land rocks [6, 13]. The most important crops produced in this region are wheat (27%), followed by dates (23%), maize (21%) and clover (9%). The average temperature is in the range of 3 - 38°C. The annual evapotranspiration ranges from 938 to 3281 mm/yr, while the average annual rainfall is about 171 mm/yr. The average relative humidity ranges from 17% in summer to 57% in winter. The average wind speed and sunshine period vary from 9.0 to 12.6 km/hr and 6.1 to 10.8 hr respectively during summer and winter seasons [9].

Jazan is one of the small regions in the Kingdom, located in the southern part of the Kingdom bordering with Yemen. It has an area of 13 thousand km² and the population of about 1.3 million respectively [6]. The region has approximately 91 thousand hectares of cultivated land [10]. The most important crop is sorghum (92% of the cultivated lands) followed by vegetables (4%) and millet (3%) [10-11]. Jazan region includes highlands and coastal belt along with the Red Sea [10]. The climate of this region is characterized as warm winter and hot summer [13]. The average temperature varies in the range of 22 - 38°C. The average relative humidity is approximately 61% in summer and 72% in winter. The average annual rainfall is approximately 104 mm/yr, while the annual evapotranspiration ranges between 1570 and 2672 mm/yr. The average wind speed and sunshine period vary in the ranges of 10.8 - 16.2 km/hr and 7.1 - 8.9 hr respectively [9].

Najran is located in the southern part of the Kingdom bordering with Yemen. It has an area of approximately 130 thousand km^2 and population of about 505 thousands, equivalent to 6.6 and 1.9% of the total area and population respectively [6]. The total cultivated area is approximately 9 thousand hectares. The most important crops are dates (36% of cultivated lands), clover (20%), citrus (19%), vegetables (15%) and wheat (8%) [10-11]. The climatic condition is arid with cold winter and hot summer seasons [13]. The temperature is in the range of 8 - 39°C. The average humidity decreases in summer, while it increases in winter season, varying in the range of 13 - 38% respectively [9]. The annual rainfall is approximately 136 mm/yr, while the evapotranspiration varies in the range 1475 - 3128 mm/yr. The average wind speed and sunshine period vary from 5.4 to 10.8 km/hr and 6.4 to 8.7 hr respectively [9].

Al-Baha is a small region, located between the Aseer and Makkah regions. It has an area and population of about 12 thousand km^2 and 411 thousands, equivalent to 0.6 and 1.5% of total area and population of the Kingdom respectively [6]. The cultivated area is approximately 2.7 thousand hectares. The most important cultivated crops in Al-Baha are: dates (52%), wheat (15%), vegetables (13%) and grapes (7%) [10-11]. The climate of this region is dry in summer with cold in winter [13]. The relative humidity varies from 18% in summer to 47% in winter. The average maximum temperature is about 38°C in summer, whereas the average minimum temperature is below 9°C in winter. The average annual rainfall is approximately 124 mm/yr, whereas the average annual evapotranspiration varies in the range of 1296 - 2796 mm/yr. The average wind speed varies between 7.2 and 10.8 km/hr, while the average sunshine period ranges between 6.3 and 8.9 hours [9].

Al-Jouf region is located in the north-west of the country. It has an area and population of approximately 85 thousand km² and 440 thousands, equivalent to 4.3 and 1.6% of total area and population of the Kingdom respectively [6]. In Al-Jouf, approximately 112 thousand hectares of land was cultivated in 2009 for producing different crops [10]. It is the third largest agricultural region in Saudi Arabia, while the first and second is the Riyadh and Qaseem regions [11]. Approximately 61, 24, 11.6 and 3.7% of the cultivated lands were used for producing cereal crops, fruits, fodder crops and vegetables respectively, while the production of wheat is the highest (e.g., 58% of the cultivated lands) [11]. The climatic condition in Al-Jouf is arid with average monthly temperature varying in the range of 3.5 - 39°C. The contribution of rain to agriculture is minimal in this region [14-15]. The average annual rainfall is approximately 58 mm/yr with an average evapotranspiration ranges from 934 to 3979 mm/yr. Average wind speed varies in the range of 6.1 – 10.9 km/hr, while the average relative humidity is below 15% in the dry months and up to 58% in winters (Table 1.1)[9].

Table 1. 1: Basic data in different regions of Saudi Arabia [6,9-11].

Regions	Population (million)	Area (1000 km^2)	Cultivated area (ha)	Temperature ((°C)	Humidity (%)	Wind speed (km/hr)	Sunshine period (hr)	Evapotranspiration (mm/yr)	Total rainfall (mm/yr)
Riyadh	6.8	380	181733	8.2 - 42.8	15 - 51	6.5-13.9	6.3 - 9.6	1168 - 3978.5	101.3
Makkah	6.9	137	33544	18.9 - 37.6	61 - 69	9-18	6.2 - 9.8	1628 - 2763	59
Madinah	1.7	150	27165	11.6 - 42.2	14 - 43	7.4 -13	5.4 -10.3	1259 - 3500	49.1
Qaseem	1.2	73	97408	6.5 - 41.4	13 - 52	7.2-12.6	5.4 -10.3	1037 - 3508	183
Eastern Region	4.1	540	55083	9.2 - 41.2	32 - 65	6.8-10	6 - 9.2	803 - 3174	166
Aseer	1.9	80	16280	7.5 - 30.5	30 - 82	7.2 -18	6.4 - 9	1102 - 2413	265
Tabouk	0.791	136	36279	3 - 37.8	21 - 50	7.2-12.6	4.8 -10.2	898 - 3124	58
Hail	0.597	120	79540	3.4 - 37.6	17 - 57	9-12.6	6.1 -10.8	938 - 3281	171
Jazan	1.3	13	91168	22.1 - 37.5	61 - 72	10.8-16.2	7.1 - 8.9	1570 - 2672	104
Najran	0.505	130	9450	8.4 - 38.5	13 - 38	5.4-10.8	6.4 - 8.7	1475 - 3128	136
Al-Baha	0.411	12	2700	8.9 - 37.9	18 - 47	7.2-10.8	6.3 - 8.9	1296 - 2796	124
Al-Jouf	0.440	85	92006	3.5 - 38.5	13 - 58	10.8-16.2	6.1 -10.9	934 - 3979	58

The Saudi geological survey [6] reported that the Eastern region has the largest area (approximately 540 thousand km^2) followed by Riyadh, Madinah, Makkah and Tabouk with about 380, 150, 137 and 136 thousand km^2 respectively (Figure 1.2). These represent about 27.6, 19.5, 7.7, 7 and 6.9% of the total area in the Kingdom respectively. The highest cultivated areas are in Riyadh (25.2%), Qaseem (13.5%), Al-Jouf (12.7%), Jazan (12.6%), Hail (11%), Eastern Region (7.6%), Tabouk (5%), Makkah (4.6%), Madinah (3.8), Aseer (2.3%), Najran (1.3%) and Al-Baha (0.4%). Further details about the cultivated areas and types of crops are presented in Chapter Two. Due to the differences in the climatic conditions and characteristics among different regions, effects of climate change on CWR are anticipated to be different.

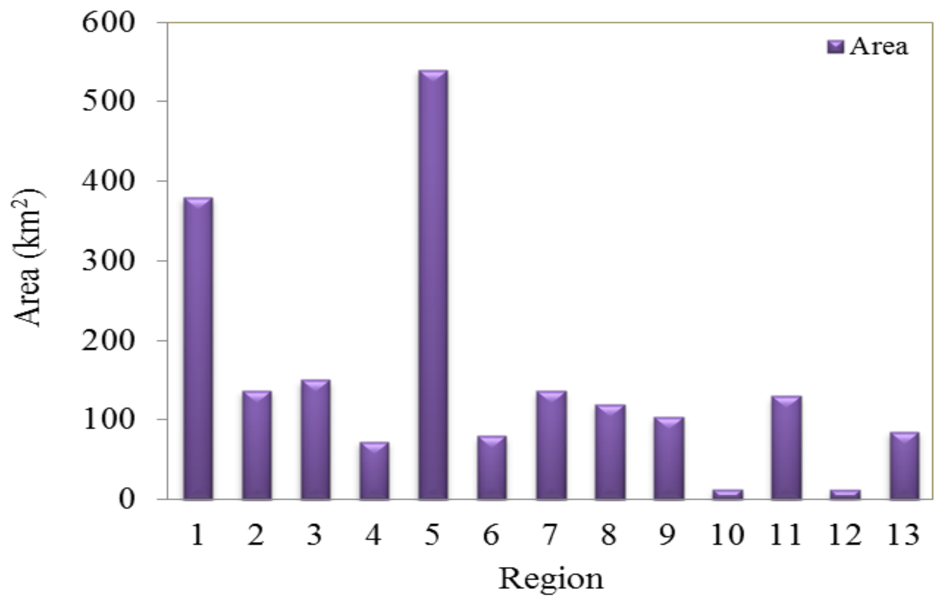

Figure 1.2: Areas of different regions in Saudi Arabia [6].

Regions [1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Northern Region, 10: Jazan, 11: Najran, 12: Al-Baha, 13: Al-Jouf]

1.3 Objective

The main objective of the research is to understand the implications of climate change on CWR from 2011 to 2050 in Saudi Arabia. The agricultural regions in Saudi Arabia are: Riyadh, Makkah, Madinah, Qaseem, Eastern region, Aseer, Tabouk, Hail, Jazan, Najran, Al-Baha and Al-Jouf. The climatic data, rainfall, planting and harvesting dates of crops, soil properties and cultivation areas in these regions are obtained from the Ministry of Agriculture (MOA), Ministry of Economy and Planning (MOEP), Saudi Geological Survey (SGS), Food and Agriculture Organization (FAO), database and Saudi Statistical Yearbook (SSYB). The current states of agricultural and climatic data will be used from the historically reported data to predict CWR for these regions. The climatic parameters for the future will be obtained from published literature. Using different combinations of climatic parameters, CWR will be predicted for four scenarios: (i) current state of temperature and rainfall (S1); (ii) the changed temperature in 2050 and current state of rainfall; (iii) changed rainfall in 2050 and current state of temperature (S3); and (iv) changed temperature and changed rainfall in 2050 (S4). Sensitivity analysis will be performed by shifting crop growing periods. Feasibility of irrigation using the non-renewable groundwater resources will also be highlighted.

1.4 Thesis Outline

This thesis has six chapters. Chapter One includes general introduction followed by the characterization of the study area. At the end of the chapter, objectives of the research are presented. Chapter Two presents the literature focusing on water resources and agriculture in Saudi Arabia, followed by the discussion on the effects of climate change on agriculture. In Chapter Three, details of the data and methodologies are discussed. Chapter Four summarizes the results under various scenarios of climatic change. The CWR for various crops are discussed in this section. Chapter Five presents the sensitivity analyses by shifting growing periods of few major crops. Strategy to conserve groundwater is discussed in this chapter. Chapter Six present the summary, conclusions and recommendations for the future study.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Anthropogenic activities in the past decades have released greenhouse gases into the environment, which might have contributed to the global warming [16-17]. Since the mid of the 19th century, temperature and precipitation have shown increasing trends [18-20]. The Intergovernmental Panel on Climate Change (IPCC) reported that the average global temperature has increased by 0.74 ± 0.18°C in the 20th century. It is expected that temperature may increase by 1.1 to 6°C in the 21st century [21-22]. The precipitation may be changed in tempo-spatial pattern, especially in the arid and semi-arid regions [16, 22-23]. The changes in climatic parameters can have significant effects on agricultural productions and CWR [24]. Past studies reported that the climate change can affect Saudi agricultural sector negatively [4, 14-15]. Increase in temperature by 1°C may change the thermal limits of the crop, which may lead to 5 - 25% decrease in crop productions [4, 25]. The Hadley Centre Global model (HadCM3) reported reduced agricultural production in arid regions in future [26]. Chowdhury and Al-Zahrani [4] predicted approximately 1.8 - 4.1°C increase in temperature from 2011 to 2050 in Saudi Arabia. Al-Zawad [8] predicted 2.5 - 5.1°C increase in temperature for the period of 2070 - 2100. Increase in temperature in such a range can increase evapotranspiration by 10.3 - 27.4% [4]. Increase in temperature, evapotranspiration, variable rainfall patterns and interactions of other meteorological parameters may have negative effects on CWR. The availability of freshwater and food security are two important issues in many countries, including Saudi Arabia [13, 15]. Understanding of the effects of climate change on CWR is important to better manage water resources. This chapter presents the research developments to date on water resources, agriculture in Saudi Arabia and highlights the implications of climate change on agriculture.

2.2 Water Resources in Saudi Arabia

Water scarcity in Saudi Arabia is an important issue [8, 14]. The average annual rainfall is very low, whereas the evaporation is very high [14-15]. Water resources in the Kingdom can be classified into four categories: surface water, groundwater (renewable and non-renewable), desalination water and treated wastewater [27]. The groundwater resources are located in the Arabian Shelf [12, 15]. These are classified into two main sources: non-renewable aquifers and renewable alluvial aquifers [7, 12, 15]. The first types are located the sedimentary cover engulfing the Arabian Shelf [7, 12]. These include Saq, Tabouk, Wajid, Minjur-Dhruma, Wasia-Biyadh, Umm Er Radhuma and Dammam-Neogene aquifers (Figure 2.1).

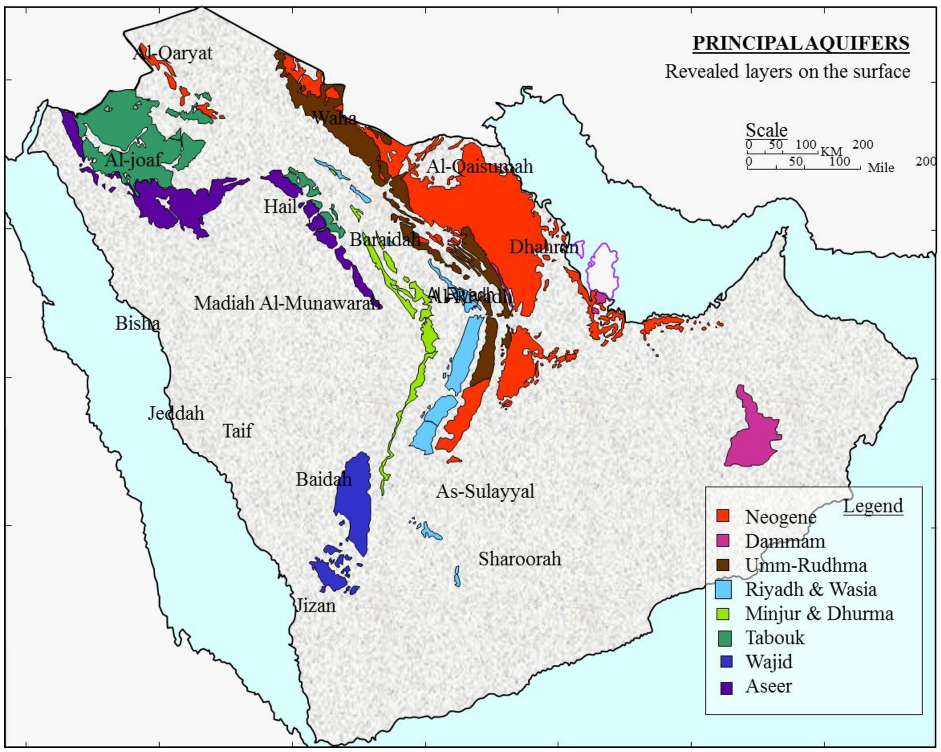

Figure 2.1: Main aquifers for groundwater in Saudi Arabia [7].

The average age of water varies from 10 to 32 thousand years, while the thickness of these aquifers ranges between 100 - 5000 m [7, 12-13]. The proven, probable and possible groundwater reserves in the non-renewable aquifers were 259.1, 415.6 and 760.6 Billion Cubic Meters (BCM) respectively [4, 28]. However, FAO [28] reported that approximately 42% of the Ministry of Agriculture and Water (MAW) estimated reserves might have been consumed by 1996. The MAW [12] indicated that the water level in the Saq aquifer was decreased by 15 m in the east of Buraydah during 1965 - 1975. It was also decreased by 5 m near the middle of Buraydah city over the period of 1979 - 1981 [12]. On the other hand water levels in and around the city of Riyadh (e.g. Minjur aquifer) was substantially declined due to increased water withdrawals [12]. The piezometric level was decreased from 45 to 170 m below the earth's surface during the period of 1956 - 1980 [12]. The Ninth Development Plan indicated that the nonrenewable groundwater extractions were 13.5 and 11.6 BCM in 2004 and 2009 respectively [27]. The other aquifers in Saudi Arabia are the secondary aquifers: Al-Jauf, Al-khuf, Al-Jilh, Sakakah, etc. (Figure 2.2) [7]. These aquifers are in the small unconfined areas, lower depth and they respond rapidly to the runoff infiltration.

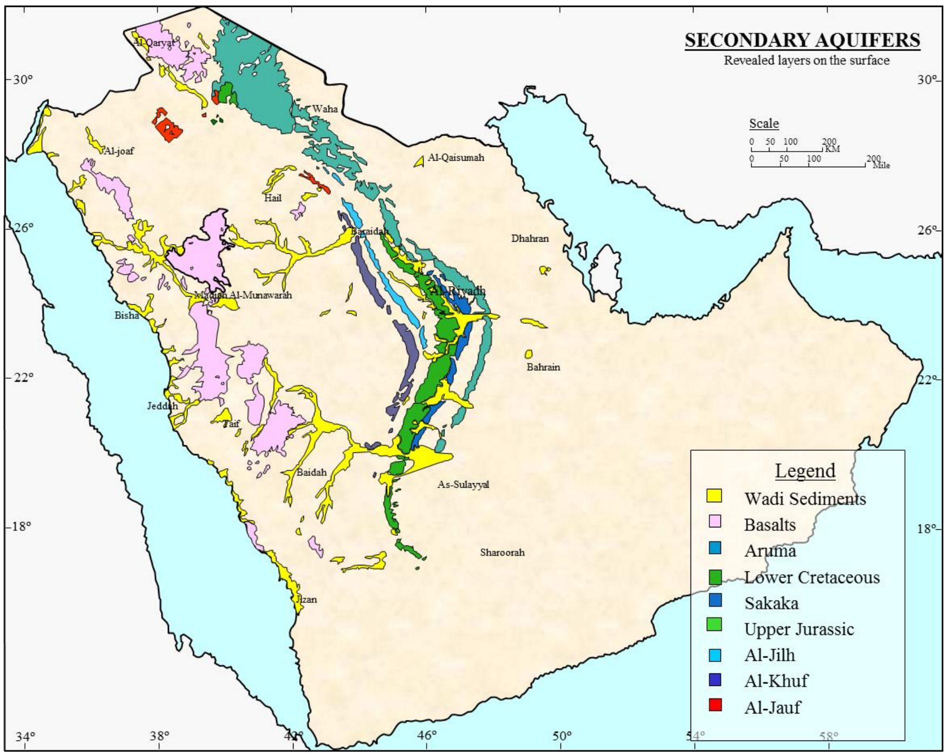

Figure 2.2: Secondary aquifers for groundwater in Saudi Arabia [7].

The source of surface water in the Kingdom is the seasonal rainfall only [27]. According to the Ninth Development Plan [27] there are 302 dams, mostly located in the South and South-Western regions of the Kingdom, storing approximately 1.4 BCM of seasonal runoff [7, 27]. The Ministry of Water and Electricity (MOWE) of Saudi Arabia [29-30] reported that a total of about 992.7 MCM/yr of surface runoff are stored and controlled by 275 dams (91% of the total dams) for groundwater recharges, while approximately of 303.5 MCM/yr and 51.5 MCM/yr are stored by the remaining of 25 and 2 dams to use for drinking and agricultural purposes respectively [7, 29 – 30].

The desalinated water in the Kingdom has been increased from 7.6 to 1048 MCM during the period of 1980 to 2009 [7, 27]. Currently, the desalination of sea water from 30 plants along the Arabian Gulf and the Red Sea coasts are the main sources of approximately 50% of total domestic water demands [27]. Some of these plants exceeded 25 years of services [7]. The government of Saudi Arabia is constructing new plants in Ras Al-Zor and Jeddah. There is a plan to increase the supply of desalinated water in future [27].

In case of treated wastewater (TWW) reuse, there has been an increasing effort in Saudi Arabia to treat domestic wastewater and recycle TWW for agricultural, landscaping and industrial reuse [7, 27]. Much of the TWW is discharged into the Red Sea, the Arabian Gulf and Wadies [7]. The Ninth Development Plan [27] reported that the reuse of TWW (without agriculture wastewater) were approximately 260 and 325 MCM/yr in 2004 and 2009 respectively, representing an increase of about 4.6% per year. There is a plan to increase this rate in future. In addition to domestic TWW, reuse of agriculture wastewater was 40 and 42 MCM in 2004 and 2009, respectively [7, 27]. There is a plan to increase this amount to 47 MCM by 2014 [27].

2.3 Agriculture in Saudi Arabia

In the decade of 1980s, the Saudi government started encouraging the farmers by distributing free lands, subsidies and interest-free loans [31]. The cultivated area increased from about 0.4 million hectares (Mha) to 1.62 Mha from 1970 to 1992 [10, 13]. The agriculture sector was enriched by many companies and farmers, who used modern commercial and traditional modes of farming, new technologies and fertilizers [13]. The Ministry of Agriculture (MOA) [11] indicated that the water supplied for irrigation, especially for wheat was about 28 thousand MCM in 1992. Wheat is considered to be the most important crop in the Kingdom [14-15]. To conserve freshwater, the government started conserving water by reducing agricultural lands and incorporating improved irrigation practices [27]. The SSYB [10] reported that 0.489, 0.468, 0.450, 0.326 and 0.196 Mha of agricultural lands were used for wheat productions in 2005, 2006, 2007, 2008 and 2009, respectively, producing approximately 2.65, 2.63, 2.56, 1.99 and 1.15 million tons (MT) of wheat respectively. However, production of 1 ton of wheat requires approximately 2492 m^3 of freshwater (2318 - 2666 m^3) [4].

Agriculture in Saudi Arabia primarily depends on climatic conditions, while water demands can vary based on the type of crops and their growing seasons [15]. In 2005 - 2009, approximately 835 - 1107 thousand hectares of land were cultivated, in which wheat was produced in 23 - 44% of the entire cultivated lands [10]. Any change in temperature and other climatic parameters can affect the evapotranspiration of the crops, which can change the CWR [4, 8, 15]. It is anticipated that the changes in the climatic parameters can be significant by 2050. For example, overall increase in temperature by 1.8 – 4.1°C has been predicted from 2011 to 2050 [4]. Recent studies have also reported increased evapotranspiration, lower soil moisture and variable rainfall patterns across the country in 2050 and 2100 [4, 8].

To predict the CWR in Saudi Arabia, data reported in the SSYB are used. The total cultivated lands were approximately 722 thousand hectares in 2009. Riyadh region had the highest cultivated area followed by Qaseem, Al-Jouf, Jazan, Hail and Eastern region (Figure 2.3). Their corresponding cultivated areas are 25.2, 13.5, 12.7, 12.6, 11 and 7.6% of the total cultivated lands respectively. More details for each region are presented in Figure 2.3. This study excluded the Northern region because of negligible cultivated area [10].

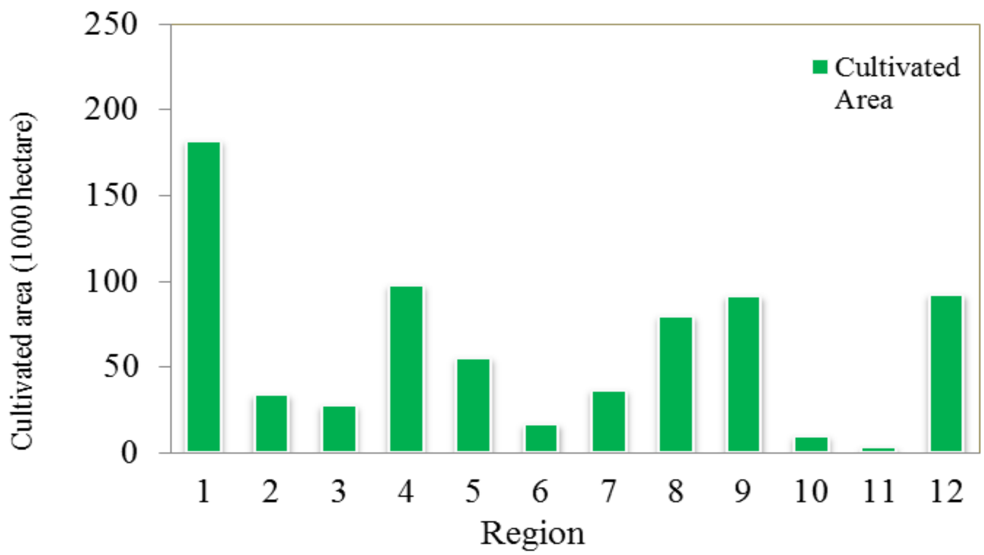

Figure 2.3: Cultivated areas for all types of crop in the Kingdom in 2009

Regions [1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

2.4 Crop Water Requirements in Saudi Arabia

Many past studies have estimated CWR in Saudi Arabia. An early study was conducted by Mustafa et al. [32] to predict CWR for wheat using the FAO modified Penman method. They found that the CWR for wheat ranged from 3790 to 6740 m^3/ha/season. Al-Omran and Shalaby [33] estimated the CWR for some field crops, vegetables and fruits in the Eastern and Central Regions using Jenen-Haise equation. The total CWR was found to be 883, 751, 1703, 2259 and 4021 mm/yr for wheat, maize, tomato, citrus and dates respectively [38]. Al-Taher et al. [34] calculated the CWR for wheat in Ad Dawadimi (south of Qaseem region) using the Blaney and Criddle method. They found that the CWR ranged from 3307 to 3829 m^3/ha/season [38]. Al-Taher et al. [35-36] calculated the CWR for wheat and date palms using Jensen-Haise equation in Najd region and the Yabrin oasis. The CWR for wheat ranges from 4448 to 6683 m^3/ha/season in Najd region, while it was found to be 26440 m^3/ha/yr for date palms cultivated in the Yabrin oasis [38]. Saif-uddin et al. [37] estimated the CWR for some crops using Penman method and agro-climatic data merged with remotely sensed data in Wadi Sirhan in Al-Jouf region. The total CWR was 34864, 6522 and 6473 m^3/ha/season for alfalfa, potato and wheat. Their growing periods were Jan.-Dec., Jan.-Apr. and Jan.-May respectively. They also reported the CWR for wheat grown during Nov.-Feb. as 3724 m^3/ha/season. Almisnid [38] predicted the CWR for wheat in Qaseem region in different farms during different planting dates using FAO Penman method. The total CWR were 3038, 3457, 3931 and 5188 m^3/ha/season during the planting dates of Nov 15, Dec 01, Dec 15 and Jan 15 (130 days of growing periods) respectively. A field study conducted by Hashim et al. [39] reported CWR for different seasonal and forage crops in

Makkah region. The CWR was predicted to be 727.8, 518.5, 452.6 and 1922.5 mm/yr for millet, wheat, maize and alfalfa crops respectively. Another recent study in Saudi Arabia Alamoud et al. [40] reported the measured ET_c in the range of 2100 - 2829 mm/yr, while the predicted ET_o were 2253 to 3024 mm/yr, resulting the average K_c in the range of 0.90 - 0.93 for Hafuf, Madinah, Makkah, Najran, Gaseem, Riyadh and Wadi Addwaser. This study demonstrated the suitability of using modified Penman equation in Saudi Arabia.

2.5 Climate Change Effects on Agriculture

Increasing water demands for irrigation is a major challenge to meet the growing food demands, especially in the arid and semi-arid regions [25-26]. Climate change is expected to result in increased temperature and reduced rainfall. Several studies have been conducted to assess the possible effects of climate change on agriculture, crop production, food security and irrigation water requirements in the arid and semi–arid regions. Different models and methods were used in these studies [41-49]. Supit et al. [41] used the output of general circulation model (GCM) and crop growth monitoring system to study the effects of climate change on the yields of wheat, potato, sugar beet and maize, cultivated during autumn, winter, spring and summer respectively. The results indicated that the effects of climate change were different based on the crop type and CO_2 emission scenarios. The crops planted in autumn, winter and spring might have the benefits due to the increase in CO_2 emission, whereas the crops planted in late spring and summer may suffer from the high temperature and droughts. Past studies reported that precipitation was the main source for agriculture sector in the North African countries except Egypt [42-43]. The temperature is expected to increase in North Africa in the range of 2 to 3°C by 2050 under the balance across all sources scenario (A1B) of IPCC, while the rainfall was predicted to decrease by 10-20% [42-43]. The agricultural productions are expected to decrease in the range of 15 - 40% in the 21st century, especially in Morocco [42]. However, IPCC [19] expected a reduction in agriculture in the range of 0.4 - 1.3% of gross domestic product (GDP) due to the effects of climate change in North Africa by the end of this century [19, 42]. Özdoğan [44] predicted the impacts of climate change on the yields of winter wheat using the data of GCM model in the semi-arid region in the northwestern Turkey. The results indicated that the yields of winter wheat might be declined in the range of 5 - 35%. This reduction is due to the increase in temperature and decline in the precipitation by 2 - 4°C and 10 - 20% respectively [44]. Connor et al. [45] evaluated the effects of climate change on irrigation, water supply variability and salinity in a semi-arid region of Murray Darling Basin in Australia. Increase in temperature by 1, 2 and 4°C can decrease the rainfalls by 5, 15 and 25% respectively. Due to this reduction in rainfall, the runoff is projected to reduce by 13, 38 and 63% in the basin respectively. This reduction in runoff is expected to decrease the average level of water supply for irrigation, increase salinity in the agriculture areas and result in loss of profit by up to 20% [45]. Many other studies investigated the effects of climate change on irrigation water requirements. Fischer et al. [46] investigated the impacts of climate change and its role in global and regional agricultural water demand for irrigation from 1990 to 2080. They used the analysis of the agro-ecological zones modeling framework (AEZ) and the database combined with the basic linked system (BLS) within a new socio-economic and reference scenario (A2r). The study projected an increase of approximately 20% in the global irrigation water requirements in 2080 due to the impacts of climate change. Approximately two-thirds of this increase could occur in the developing countries. The study found that lowering the rate of climate change could reduce the irrigation water requirements by about 40% [46]. However, Döll [47] predicted an increase in the irrigation water requirements in the range of approximately 5 - 8% by 2070 using GCM model [47]. Mall et al. [48] reported that the changes in temperature may range between 1° and 4°C in India. While the rise in temperature by 4°C caused a decrease in runoff by 2 - 8%, no significant change in rainfall over India (e.g. decreasing or increasing in some locations) was anticipated. It also projected that the irrigation water requirements could increase in the range of about 3.5 - 5% and 6 - 8% by 2025 and 2075, respectively due to climate impacts. This might cause a decline in groundwater, where about 52% of water supply for irrigation is obtained from groundwater resources. The study conducted by Ghazala and Mahmood [49] in Pakistan also predicted the CWR for wheat under different temperature. Averages of increase in CWR were 11, 19 and 29% for temperature increase of 1, 2 and 3°C respectively.

Data on agricultural water uses and water availability demonstrate that the current state of agricultural activities may not be continued for long-term in Saudi Arabia. For better management of available resources and agricultural productions, it is important to understand CWR, current level of water supplies and possible effects of climate change in future. This study will assist in the efficient use of non-renewable water and minimize water withdrawal from these sources. This will further provide an opportunity in setting rules and procedures for rationalization of water consumption in agricultural areas.

CHAPTER 3

METHODOLOGY

3.1 General

The CWR can be predicted by several methods. To better estimate CWR under various scenarios of climatic changes, FAO recommended using CROPWAT software [50-51]. The CWR depends on climatic conditions, crop area and type, soil classification, growing seasons and crop production frequencies [51]. The required data were obtained from published literature [4, 9–11, 52-57]. The CROPWAT software system has been widely used to determine reference evapotranspiration (ET_o), effective rainfall (P_{eff}) and actual evapotranspiration (ET_c). The CWR for each crop was predicted under the S1 - S4 scenarios. This chapter presents the integrations of climatic and crop parameters. The chapter also discusses the CROPWAT software system and the FAO method of predicting CWR.

3.2 Climatic Parameters

The data required for CROPWAT software are the climatic parameters (e.g., maximum and minimum temperature, wind speed, sunshine period, humidity and rainfall), planting and harvesting dates of crops, soil type and cultivated areas. The historical climatic data were obtained from FAO database and other published literature those have summarized the weather station data from all regions in Saudi Arabia[9].These data were used to predict CWR for the current climatic conditions. To predict CWR for 2050, values of climatic parameters were obtained from past studies [4]. The climatic parameters are discussed below.

3.2.1 Temperature

The maximum and minimum temperature varied widely from region to region. The average annual temperature ranges from 11.8 to 34.5°C in different regions. The monthly averages of minimum and maximum temperatures for different regions are presented in Table 3.1. This table shows that the maximum and minimum temperature increase gradually from Jan. to the peak values in Jul. and/or Aug. and then decrease gradually till Dec. These values range between 3 and 42.8°C over the Kingdom [9]. The data in Table 3.1 have been used in the S1 and S3 scenarios.

Table 3. 1: Monthly average temperature in 2011 for each region in Saudi Arabia

Month	Maximum and Minimum Temperature (°C) for Each Region																							
	Riyadh		Makkah		Madinah		Qaseem		Eastern Region		Aseer		Tabouk		Hail		Jazan		Najran		Al-Baha		Al-Jouf	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Jan	8.2	20.2	18.9	28.5	11.6	23.6	6.5	18.4	9.2	19.2	7.5	19.9	3	17.2	3.4	15.9	22.1	29.9	8.4	24.7	8.9	24.9	3.5	14.9
Feb	10.3	22.9	18.9	29.3	13.3	26.1	8.2	21.6	10.5	21.9	8.6	22	5.9	21	5.5	19.6	22.6	30.4	10.6	26.7	10.9	27.4	6.2	18.2
Mar	14.4	27.6	20.5	31	17.4	30.2	12.3	26.4	14.3	26.2	10.8	23.1	8.5	24.1	9.2	23	24.2	32.4	14	29	14.7	30	9.9	22.8
Apr	18.9	32.3	22.2	33.3	20.8	33.9	16.9	30.9	19.4	31.5	11.9	25.1	14.1	30.4	14.3	28.3	26.1	34.9	17.5	32.3	17.2	32.4	16.1	28.5
May	24.2	38.7	24.5	35.4	24.9	38.9	22	36.9	23.9	36.8	14.3	27.8	17.8	32.7	18.9	33.5	28.1	37	21.4	35.7	20.8	35.5	20.7	33.1
Jun	26.2	41.5	25.3	36.4	27.9	41.7	23.7	40.5	27.3	39.8	15.4	30.4	21.7	37.1	21.3	36.6	29.6	37.5	21.8	38.5	22.4	38.1	24	36.8
Jul	27.4	42.8	26.8	37.6	28.4	39.3	24.5	41.4	29.3	41.2	16.6	29.5	22.3	37.6	22.4	37.4	29.8	37.1	23.7	38.5	24.1	37.9	26.1	38.4
Aug	27	42.5	27.2	37.1	28.7	42.2	24.4	41.1	28.4	40.2	16.4	29.7	22.2	37.8	21.6	37.6	29.7	37.2	23.7	38.2	28.8	37.9	25.8	38.5
Sep	24.1	40.1	26.1	35.8	27.1	41	22.4	39.4	26.1	38.8	14.3	28.3	19.5	36.3	19.7	36.4	28.7	37.1	19.9	36.4	20.1	36	23.9	37.3
Oct	19.2	34.6	24.2	34.9	21.9	36.4	17.2	33.9	21.2	33.2	10.6	25	14.8	30.7	14.1	30.9	25.7	36	14	31.3	14.9	31.6	18.2	32
Nov	14.3	27.4	22.3	32.5	17.2	29.7	12.4	25.8	15.1	26.5	8.1	22.9	9	23.8	9.4	23.2	23.8	33.1	10.4	27.3	11.8	28.2	10.9	22.5
Dec	9.4	21.7	20	29.7	12.9	25	7.8	20.1	10.4	21.6	7	20.9	4.1	18.3	4.5	17.5	22.2	31.9	9.5	26.5	8.7	25	4.9	16.9
Average	18.6	32.7	23.1	33.5	21	34	16.5	31.4	19.6	31.4	11.8	25.4	13.6	28.9	13.7	28.3	26.1	34.5	16.2	32.1	16.9	32.1	15.8	28.3

The data of projected temperature in 2050 were used to predict CWR for the S2 and S4 scenarios. The projected temperature in 2050 for all regions was obtained from literature [4]. An interpolation was done on these data to obtain the predicted temperature for the agricultural areas in each region. For example, temperature in Al-Jouf region in 2050 is expected to increase by 2.58 and 2.27°C at locations A (lat. 27.50N; lon.33.75E) and B (lat. 30N; lon. 56.25E) respectively. Using the linear interpolation, increase in temperature in Jan. for Al-Jouf was obtained as:

$$Temp. = 2.58 - \frac{(27.5 - 29.78) \times (2.58 - 2.27)}{(27.5 - 30)} = 2.29^{o}C$$

Same procedure was followed for each month in each region. The projected increase in temperature in Riyadh, Makkah, Madinah, Qaseem, Eastern region, Aseer, Tabouk, Hail, Jazan, Najran, Al-Baha and Al-Jouf in 2050 are in the range of approximately 2.1 - 3.8°C, whereas the average annual increase is expected to be in the range of 2.6 - 2.8°C. These data were added to the current temperature to obtain the expected temperature in 2050 (Table 3.2). The projected temperature in 2050 may range between 5.5 and 45.9°C over the Kingdom (Table 3.2) [9].

Table 3. 2: Predicted monthly average temperature in 2050 for each region in Saudi Arabia

Month	Maximum and Minimum Temperature (°C) for Each Region																							
	Riyadh		Makkah		Madinah		Qaseem		Eastern Region		Aseer		Tabouk		Hail		Jazan		Najran		Al-Baha		Al-Jouf	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Jan	10.4	22.4	21.3	30.9	13.8	25.9	8.8	20.7	11.5	21.5	10	22.4	5.5	19.7	5.6	18.1	24.4	32.2	10.9	27.2	11.3	27.3	5.8	17.2
Feb	12.5	25.1	21.2	31.6	15.6	28.4	10.5	23.9	12.8	24.2	11	24.4	8.4	23.5	7.7	21.8	24.7	32.5	13.1	29.2	13.1	29.6	8.5	20.5
Mar	16.5	29.7	22.7	33.2	19.5	32.3	14.5	28.6	16.5	28.4	13.1	25.4	10.8	26.4	11.3	25.1	26.4	34.6	16.3	31.3	16.9	32.2	12	24.9
Apr	21	34.4	24.3	35.4	22.9	36	19.1	33.1	21.7	33.7	14.1	27.3	16.4	32.7	16.5	30.5	28.4	37.2	19.7	34.5	19.4	34.6	18.4	30.8
May	26.3	40.8	26.6	37.5	27	41	24.2	39.1	26.1	39.1	16.5	30	20.2	35.1	21.1	35.7	30.4	39.3	23.5	37.8	23.1	37.8	22.9	35.3
Jun	28.7	44	27.8	38.9	30.4	44.2	26.2	43	29.9	42.3	17.9	32.9	24.3	39.6	23.8	39.1	32.4	40.3	24.1	40.8	25.3	41	26.4	39.2
Jul	30.4	45.9	29.8	40.6	31.4	42.3	27.4	44.3	32.2	44.1	19.4	32.3	25.2	40.5	25.3	40.3	32.9	40.2	26.4	41.1	27.4	41.2	28.9	41.2
Aug	30.3	45.8	30.3	40.2	31.9	45.4	27.6	44.3	31.6	43	19.5	32.8	25.4	41	24.9	40.9	32.9	40.4	26.7	41.2	32.1	41.2	29.2	41.9
Sep	27.9	43.9	29.6	39.3	30.8	44.7	26	43	29.7	42.3	17.7	31.7	23	39.8	23.4	40.1	32.1	40.5	23.2	39.7	23.8	39.7	27.4	40.8
Oct	22.8	38.2	27.7	38.4	25.4	39.9	20.6	37.3	24.5	36.5	14	28.4	18.1	34	17.5	34.3	29.1	39.4	17.2	34.5	18.7	35.4	21.4	35.2
Nov	17	30.1	25.1	35.3	19.9	32.4	15.2	28.6	17.9	29.3	11	25.8	11.9	26.7	12.1	25.9	26.8	36.1	13.2	30.1	14.8	31.2	13.6	25.2
Dec	11.8	24.1	22.5	32.2	15.3	27.4	10.3	22.6	12.9	24.2	9.5	23.4	6.7	20.9	6.8	19.8	24.8	34.5	12	29	11.3	27.6	7.3	19.3
Average	21.3	35.4	25.7	36.1	23.7	36.7	19.2	34	22.3	34.1	14.5	27.8	16.3	31.7	16.3	31	28.8	37.3	18.9	34.7	19.8	34.9	18.5	31

3.2.2 Wind Speed

Past studies [4, 15] have reported that the changes in wind speed in future might not be significant. The data of current state of wind speed was obtained from FAO database [9]. Table 3.3 shows that the average yearly wind speed varies in the range of 7.8 – 14.1 km/hr over the country. However, there is a significant variability in the average monthly and yearly wind speed from region to region. For instance, monthly average wind speeds in the regions of Makkah, Jazan and Al-Jouf are higher (e.g., 9 - 18 km/hr) than those in the other regions (e.g., 5.4 - 14 km/hr) (Table 3.3). The minimum yearly average wind speed is 13.2 km/hr in these regions, while the maximum in the other regions is 10.7 km/hr (Figure 3.1).

Table 3. 3: Monthly average wind speed for each region in Saudi Arabia

Region	Average Wind Speed (km/hr)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly Average
Riyadh	10.2	10.2	10.2	13.9	12.0	13.9	13.0	11.1	10.2	8.3	6.5	7.4	10.6
Makkah	16.2	18.0	14.4	14.4	14.4	14.4	12.6	14.4	18.0	9.0	10.8	12.6	14.1
Madinah	7.4	9.3	11.1	13.0	11.1	9.3	11.1	9.3	7.4	7.4	9.3	7.4	9.4
Qaseem	9.0	9.0	10.8	12.6	12.6	10.8	10.8	9.0	7.2	9.0	9.0	9.0	9.9
Eastern Region	6.3	7.8	8.6	7.2	8.4	10.0	9.3	8.3	6.8	6.8	7.0	7.2	7.8
Aseer	12.6	12.6	12.6	12.6	12.6	9.0	10.8	9.0	10.8	9.0	7.2	9.0	10.7
Tabouk	9.0	9.0	10.8	12.6	10.8	10.8	10.8	9.0	9.0	9.0	7.2	7.2	9.6
Hail	10.8	10.8	12.6	12.6	10.8	10.8	10.8	9.0	9.0	9.0	9.0	9.0	10.3
Jazan	12.6	12.6	12.6	12.6	12.6	14.4	16.2	16.2	12.6	10.8	12.6	12.6	13.2
Najran	9.0	9.0	10.8	9.0	10.8	10.8	9.0	9.0	10.8	5.4	9.0	7.2	9.2
Al-Baha	7.2	9.0	10.8	10.8	9.0	7.2	9.0	9.0	9.0	9.0	7.2	7.2	8.7
Al-Jouf	14.4	14.4	16.2	16.2	12.6	14.4	14.4	12.6	12.6	10.8	12.6	10.8	13.5

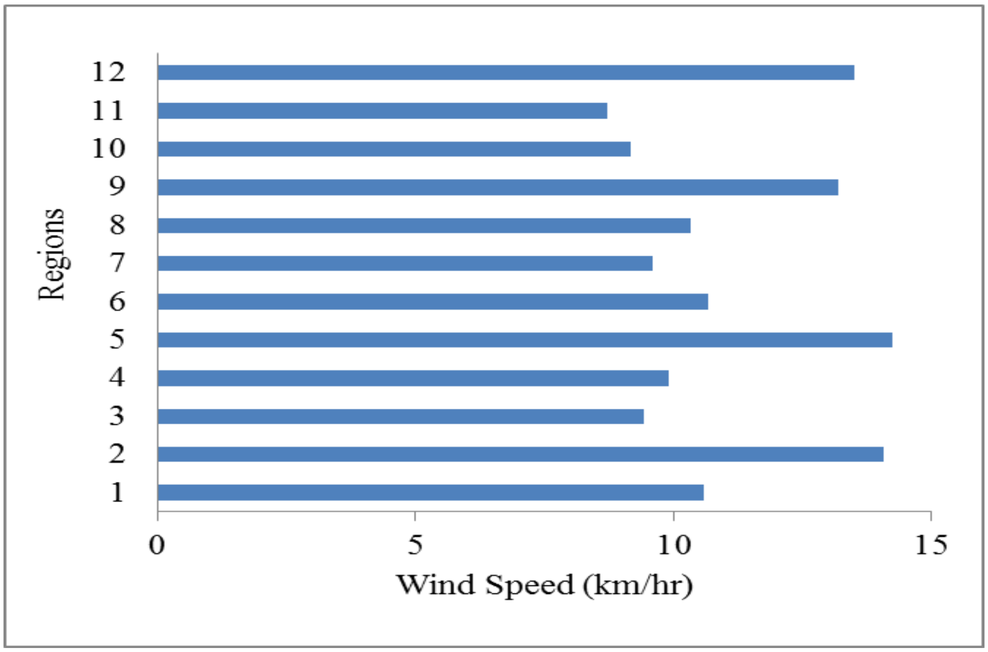

Figure 3.1: Yearly average wind speed for each region in Saudi Arabia

Regions [1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

3.2.3 Precipitation

The rainfall distributions were different from region to region [4, 9]. The total annual rainfall varied in the range of 49 mm/yr in Madinah to 264 mm/yr in Aseer region (Table 3.4), while the average annual rainfall is about 123 mm/yr. The variability of rainfall is significant in these regions (Table 3.4). The rainfall during the period of Oct. - May is higher than the rainfall in the other months. The rainfall is very small and/or almost zero in the months of Jun. – Sep. in all regions except Aseer and Jazan (Table 3.4)

The rainfall in 2050 was obtained from the study conducted by Chowdhury and Al-Zahrani [4]. The projected rainfall changes (increase/decrease) in 2050 are presented in Figure 3.2. The expected values of rainfall in 2050 are presented in Table 3.5. There might be an increase in rainfall in some months, which can reduce the CWR for those months. The data from Table 3.5 has been incorporated to predict CWR for the S3 and S4 scenarios.

Table 3. 4: Monthly average rainfall for each region in Saudi Arabia.

Region	Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Riyadh	11.3	10.1	24.0	29.4	7.8	0.1	0.4	0.6	0.1	1.2	5.6	10.7	101.3
Makkah	12.0	5.0	3.0	2.0	1.0	0.0	0	0	0	1.0	18.0	17.0	59.0
Madinah	8.0	1.2	8.3	11.9	4.6	0.4	0.2	0.3	0.1	1.1	9.2	3.8	49.1
Qaseem	18.0	10.0	59.0	37.0	4.0	0.0	0.0	0.0	0	4.0	20.0	31.0	183.0
Eastern Region	25.6	25.7	39.1	16.9	9.0	0	0	1.3	0	4.9	23.0	20.1	165.7
Aseer	8.0	11.0	68.0	53.0	37.0	6.0	25.0	30.0	6.0	3.0	11.0	6.0	264.0
Tabouk	12.0	3.0	7.0	3.0	4.0	0	0	0	0	7.0	15.0	7.0	58.0
Hail	27.0	12.0	20.0	26.0	13.0	0	0	0	0	10.0	49.0	14.0	171.0
Jazan	4.0	3.0	11.0	18.0	3.0	4.0	6.0	20.0	6.0	4.0	9.0	16.0	104.0
Najran	3.0	12.0	71.0	35.0	4.0	0	0	1.0	1.0	0	0	9.0	136.0
Al-Baha	4.0	4.0	44.0	43.0	11.0	2.0	1.0	7.0	0	3.0	0	5.0	124.0
Al-Jouf	9.0	3.0	8.0	14.0	0	2.0	0	0	0	10.0	4.0	8.0	58.0

Table 3. 5: Predicted monthly average rainfall for each region in Saudi Arabia in 2050

Region	Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Riyadh	16.0	3.9	19.4	27.8	8.2	0	0	4.2	13.2	1.7	3.4	11.7	109.5
Makkah	18.2	7.0	3.4	1.9	0.5	0	0	5.7	10.8	6.9	18.2	18.7	91.3
Madinah	13.5	0	4.9	10.3	4.7	0	0	3.7	12.2	1.5	7.5	5.3	63.6
Qaseem	30.8	13.2	59.2	33.0	2.2	0	0	1.4	3.0	3.9	21.9	35.9	204.5
Eastern Region	38.8	31.3	39.7	12.1	6.8	0	0	2.4	2.3	4.9	24.9	24.9	188.2
Aseer	13.2	16.4	61.4	53.7	35.9	5.1	22.7	39.2	25.4	22.4	11.5	11.4	318.3
Tabouk	26.7	14.7	9.2	0	0.7	0	0	0.4	0.4	6.9	17.4	11.9	88.3
Hail	34.0	3.2	13.2	24.1	13.4	0	0	2.5	7.2	11.6	47.1	15.4	171.8
Jazan	0	0	4.9	16.6	2.5	3.0	0	43.5	77.9	77.2	37.2	23.0	285.8
Najran	18.0	25.3	64.3	35.9	2.5	0	0	5.9	9.9	6.0	0	12.8	180.6
Al-Baha	0	0	37.6	43.3	10.8	3.3	0	26.6	45.1	55.1	5.0	14.3	241.1
Al-Jouf	17.0	0	6.0	10.4	0	2.0	0	2.4	7.2	11.5	2.2	8.2	67.0

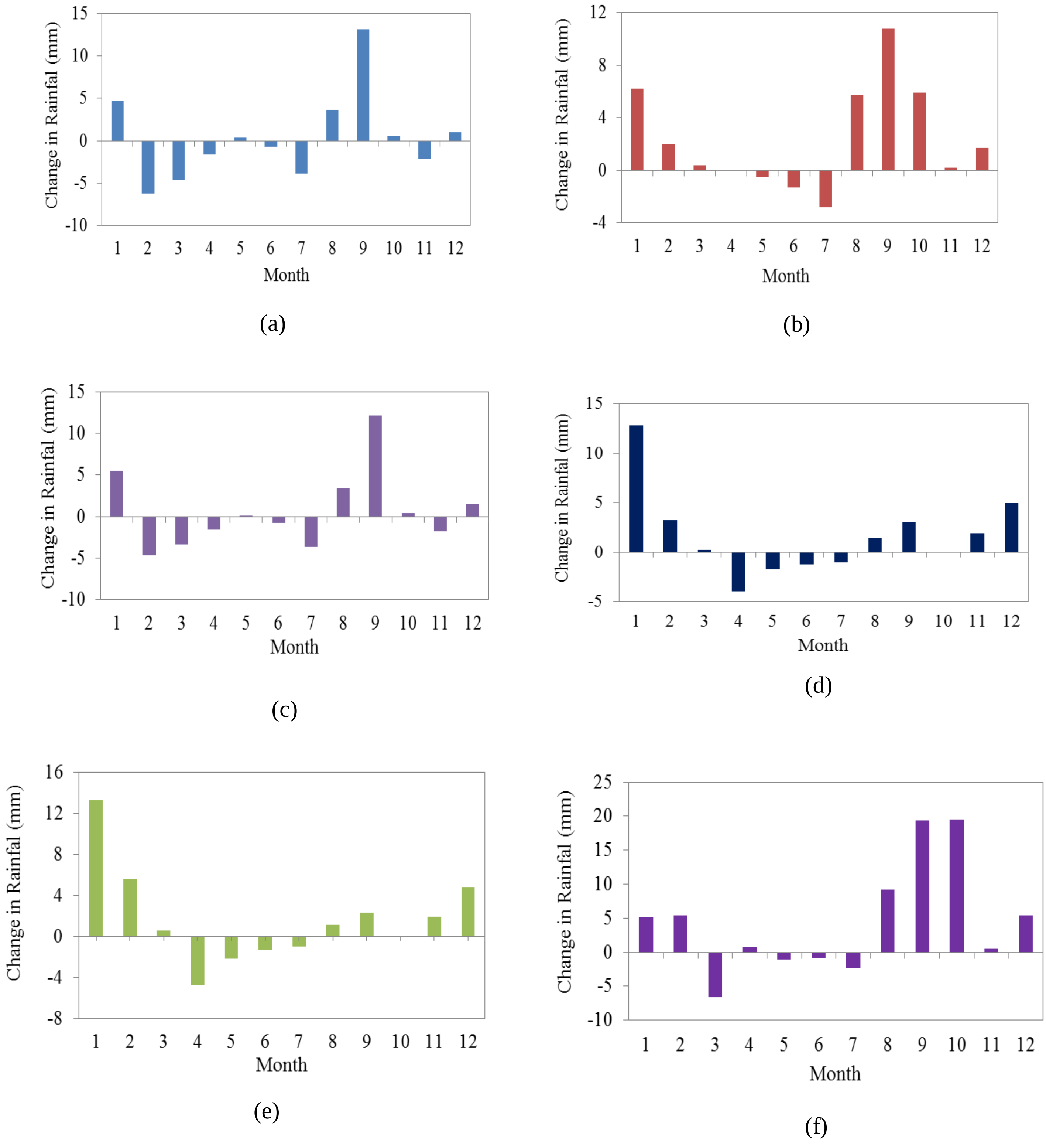

Figure 3.2: Expected change in rainfall in 2050 for regions in Saudi Arabia

(a): Riyadh, (b): Makkah, (c): Madinah, (d): Qaseem, (e): Eastern region, (f): Aseer.

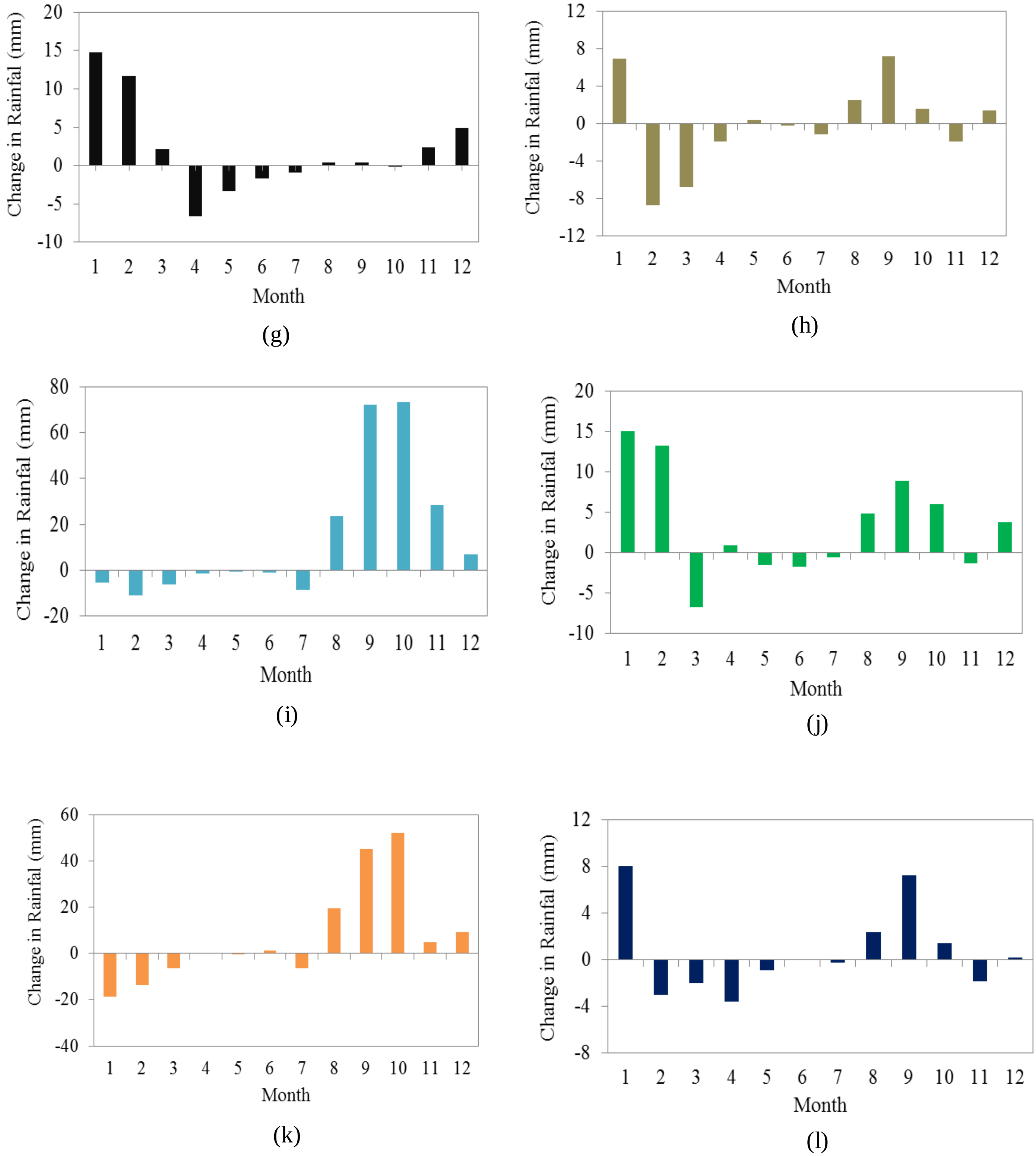

Figure 3.2 continued:

(g) Tabouk, (h) Hail, (i) Jazan, (j) Najran,(k) Al-Baha, (l) Al-Jouf and [1-12: Jan. - Dec.]

3.2.4 Relative Humidity

The data of relative humidity are presented in Table 3.6. This table shows that the average relative humidity in the Kingdom varies from region to region. While Jazan had the highest average annual relative humidity (65%), the region of Najran had the lowest in the country (26%). The average annual relative humidity in Makkah, Aseer and Eastern region are about 63, 48 and 47.3% respectively. It is almost 30% in the central part (e.g., Riyadh and Qaseem). In the north, west and southwest, the average annual relative humidity varies in the range of 28 - 33%. The data also showed that the average monthly relative humidity in the months of May – Sep. is lower than those in the other months (Oct. – Apr.) in all regions [9]. The relative humidity has been predicted to decrease in future [4]. Chowdhury and Al-Zahrani [4] predicted a decrease in the average relative humidity between 0.8 and 2.3% in 2050 in the most part of the Kingdom.

Table 3. 6: Monthly average relative humidity for each region in Saudi Arabia

Region	Relative Humidity (%)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Riyadh	51.0	48.0	37.0	33.0	22.0	15.0	16.0	16.0	17.0	22.0	44.0	44.0	30.0
Makkah	64.0	63.0	63.0	61.0	63.0	62.0	59.0	62.0	69.0	68.0	64.0	62.0	63.0
Madinah	43.0	43.0	27.0	25.0	19.0	14.0	17.0	19.0	18.0	23.0	41.0	42.0	28.0
Qaseem	52.0	43.0	36.0	31.0	24.0	16.0	16.0	13.0	17.0	23.0	38.0	51.0	30.0
Eastern Region	65.0	58.3	52.7	44.7	39.0	32.0	35.0	36.0	40.7	48.3	55.3	61.3	47.3
Aseer	61.0	59.0	59.0	53.0	45.0	35.0	39.0	44.0	30.0	37.0	51.0	59.0	48.0
Tabouk	46.0	40.0	34.0	29.0	24.0	22.0	21.0	23.0	25.0	31.0	42.0	50.0	32.0
Hail	57.0	44.0	38.0	36.0	26.0	17.0	17.0	17.0	18.0	28.0	47.0	55.0	33.0
Jazan	72.0	72.0	61.0	66.0	62.0	62.0	61.0	62.0	58.0	65.0	70.0	71.0	65.0
Najran	37.0	36.0	29.0	33.0	17.0	14.0	13.0	25.0	16.0	19.0	28.0	38.0	26.0
Al-Baha	38.0	36.0	35.0	35.0	26.0	20.0	18.0	20.0	19.0	19.0	31.0	47.0	29.0
Al-Jouf	50.0	37.0	32.0	25.0	16.0	14.0	13.0	14.0	16.0	27.0	45.0	58.0	29.0

3.2.5 Net Radiation

The net radiation was estimated using the data from the FAO database [9]. According to Allen et al [50], radiation can be determined from the actual duration of bright sunshine period per day. The data of radiation are presented in Table 3.7. These data show that the radiation in summer (Jun. – Aug.) is higher than those in the other months, varying in the range of 19.1 - 26.2 Mega Joules per square meter per day ($MJ/m^2/day$). In general, the average annual radiation ranges between 18.2 and 19.8 $MJ/m^2/day$ in the entire country [9].

Table 3. 7: Monthly average radiation for each region in Saudi Arabia

Region	Radiation ((MJ/m²/day))												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Riyadh	13.8	16.5	18.3	20.4	21.7	24.4	24.0	23.4	21.0	17.9	14.9	12.7	19.1
Makkah	14.1	16.9	19.4	22.1	24.1	24.6	24.3	23.4	21.0	18.3	15.5	14.1	19.8
Madinah	13.9	17.1	17.8	19.7	22.5	25.5	25.3	24.4	20.8	18.2	15.7	11.7	19.4
Qaseem	13.4	16.7	17.5	19.6	22.4	25.5	25.2	24.2	20.6	17.8	15.2	11.3	19.1
Eastern Region	12.6	15.0	16.9	19.2	22.3	23.8	23.4	22.6	19.9	17.4	13.8	11.8	18.2
Aseer	16.4	19.1	21.6	23.2	20.5	21.8	19.6	19.2	20.4	19.3	18.1	15.2	19.5
Tabouk	12.7	15.6	19.2	24.2	21.9	20.2	22.5	24.3	20.2	17.1	13.3	10.1	18.4
Hail	12.6	16.0	18.2	21.7	24.2	25.4	26.0	24.5	20.7	16.7	14.7	11.7	19.4
Jazan	16.7	19.3	21.9	23.2	20.5	21.5	19.4	19.2	20.5	19.3	18.5	15.2	19.6
Najran	16.6	19.3	21.7	23.2	20.4	21.7	19.5	19.2	20.5	19.4	18.4	15.4	19.6
Al-Baha	15.9	18.7	21.4	23.0	20.6	21.9	19.5	19.1	20.3	19.4	17.6	14.4	19.3
Al-Jouf	11.9	15.4	17.8	21.5	24.2	25.4	26.2	24.3	20.3	16.1	14.1	11.1	19.0

3.3 Crop Parameters

3.3.1 Crop Growth Stage Coefficient (K_c)

Crop growth stage coefficient (K_c) is the property of crop that determines crop evapotranspiration (ET_c). It is a dimensionless. In Saudi Arabia, it may ranges between 0.1 and 1.2 [50]. The K_c was obtained from FAO database [9, 50]. The growth stages for different crops and K_c are shown in Table 3.8. The values of K_c for wheat are 0.55, 1.15 and 0.30 at the initial stage, mid-season and the late season respectively (Figure 3.3). The value of 0.55 remains constant till the end of the 20 days of the initial stage. It increases gradually to 1.15 during the development stage of 30 days. Then, it remains constant (1.15) during the mid-season of 50 days of growing period. It declines to 0.30 during the late season of 30 days of growing period. The K_c values for wheat, millet, sorghum, maize, barley, tomato, potato and other vegetables increase to more than unity in the development stage and mid-season, indicating that ET_c is higher than ET_o, leading to increased CWR in the development and mid-season stages. The value of K_c is generally higher during the mid-season period of the crop growing seasons [50]. The values of K_c for the other crops are presented in Table 3.8.

Table 3. 8: Growing stages and crop growth stage coefficient (K_c)

Crops	Growing stages (days)				Total stage (days)	Crop growth stage coefficient (K_c)		
	Initial	Develop.	Mid-season	Late season		Initial	Mid-season	Late season
Wheat	20	30	50	30	130	0.55	1.15	0.30
Maize	20	35	40	30	125	0.30	1.20	0.35
Millet	15	25	40	25	105	0.30	1.00	0.30
Sorghum	20	35	40	30	125	0.30	1.00	0.55
Barley	15	25	50	30	120	0.30	1.15	0.25
Tomato	30	40	45	30	145	0.60	1.15	0.80
Potato	25	30	45	30	130	0.50	1.15	0.75
Other vegetables	20	30	30	15	95	0.70	1.05	0.95
Clover	150	30	150	35	365	0.40	0.95	0.90
Dates	140	30	150	45	365	0.90	0.95	0.95
Citrus	60	90	120	95	365	0.70	0.65	0.70
Grapes	150	50	125	40	365	0.30	0.70	0.45

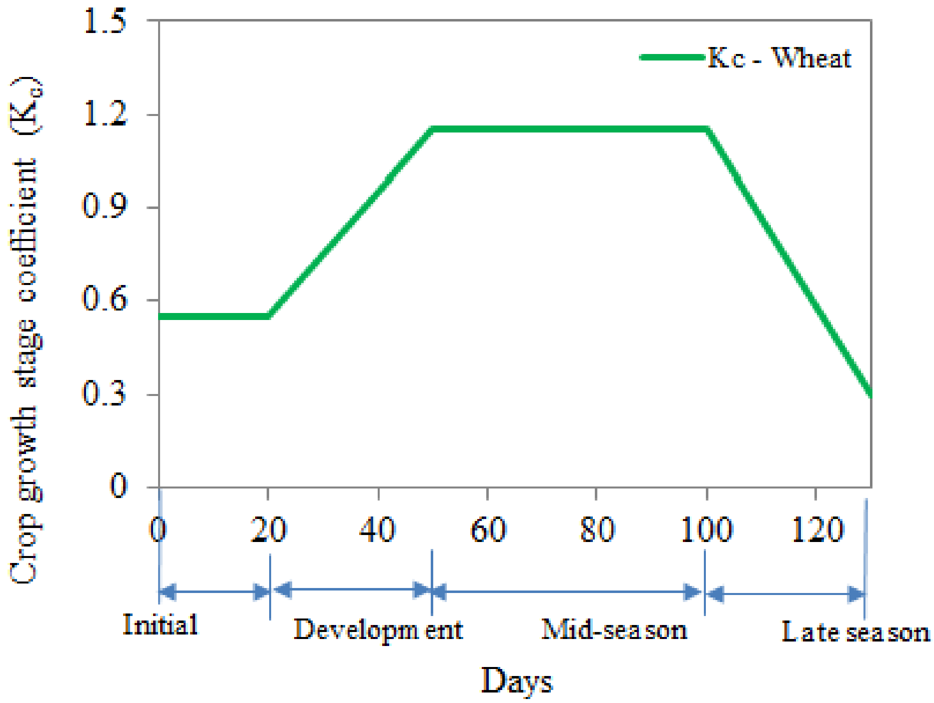

Figure 3.3: Typical crop growth stage coefficient (K_c) for wheat.

3.3.2 Soil Type

The soil surface in most of the agricultural regions in Saudi Arabia is sandy loam and or loamy sand [49], which can be characterized as light sand soil following the FAO classification [9]. The soil data includes soil texture, total available soil moisture, maximum infiltration rate, maximum rooting depth and initial soil moisture depletion. These data were obtained from literature [9, 13].

3.3.3 Planting and Harvesting Dates

Identification of the best planting date for a crop is the key point for successful crop production in any agricultural area. Selection of planting date depends on many factors, such as type of crop, climate conditions, type of soil and crop yields. Crop can be grown in more than one planting date in the same season [52]. Temperature is one of the most important factors in selecting the best planting date because of its effects on the processes carried out by the plant, such as absorption, photosynthesis, transpiration, effects on crop growth and productivity [52-53]. Cultivation of crops in a timely manner is important to get maximum productivity per unit area [52]. Due to the importance of selecting the best planting date, data of the best planting dates for different types of crops in the Kingdom were collected from SSYB, MOA and past studies [4, 10-11, 52-57]. These data show that the best planting date for wheat starts from early Nov. to the end of Jan. (01 Nov. – 30 Jan.) [9, 32-39, 53, 55]. Planting date for millet starts from the early of Jan. to the end of Apr. (01 Jan. – 30 Apr.) [9, 39, 53]. Sorghum is cultivated in late Jan. and early Feb. or in Apr. in Jazan, Central, Aseer, Hail and Madinah [9, 53]. Maize grows in the Kingdom in early Apr. or early Aug. In Jazan, best date for planting maize is the month of Oct. Barley is sowed at early of Nov [9, 53]. Tomato grows in Jan – Apr, Feb – Apr, Mar - May and/or July – Aug., while potato is cultivated within the period of Jan. – Apr. Most of the vegetables are cultivated in the period of 01 Jan. – 30 April [9, 37, 52-55]. Clover dates, citrus and grapes are perennial crops. The growing periods for these crops are almost one year [9, 39-40, 53, 55-57]. Further details of planting dates periods are presented in Table 3.9.

Table 3. 9: Planting dates periods for crops in each region in Saudi Arabia

Crop	Planting dates periods												Total growing periods (days)	Reference
	Riyadh	Makkah	Madinah	Qaseem	Eastern Region	Aseer	Tabouk	Hail	Jazan	Najran	Al-Baha	Al-Jouf		
Wheat	Nov-Jan	Nov- Jan	Nov- Jan	Nov- Jan	Nov- Jan	Nov- Jan	Nov- Jan	Nov- Jan	-	Nov- Jan	Nov- Jan	Nov- Jan	120-140	[9, 32-39, 53, 55]
Millet (Grains)	-	Jan-Apr	Jan-Apr	-	-	Nov- Jan	-	-	Jan- Apr	-	Jan- Apr	-	105	[9, 39, 53]
Sorghum	Jul-15 Aug	Jan-Feb	-	-	-	01-30 Apr	-	-	01-30 Apr	-	01-30 Apr	-	125	[9, 53]
Maize	Mar- Apr	Mar- Apr	Mar- Apr	15 Mar-15 Apr	Mar-Apr	Mar Apr	Mar-Apr	Mar-Apr	01-30 Oct	-	Mar- Apr	01-30 Aug	125	[9, 53]
Barley	01-30 Nov	01-30 Nov	01-30Nov	01-30 Nov	01-30 Nov	01-30 Nov	01-30 Nov	01-30 Nov	01-30 Nov	01-30 Nov	01-30 Nov	01-30 Nov	120	[9, 53]
Tomato	Feb-Apr	Jan- Apr	Feb-Apr	Feb- Apr	Feb-Apr	Feb-Apr	Mar-Apr	Mar-Apr	Jan- Apr	Feb-Apr	Mar-May	Mar-Apr	145	[9, 37, 52- 55]
Potato	Jan- Mar	Jan-Feb	Jan-Feb	Jan-Feb	Jan-Feb	Jan-Apr	Jan-Mar	Jan- Mar	-	Jan-Feb	Jan-Mar	Jan-Mar	130	[9, 37, 52-55]
Other vegetables	Jan- Apr	Jan-Apr	Jan-Apr	Jan-Apr	Jan-Apr	Jan-Apr	Jan-Apr	Jan-Apr	Jan-Apr	Jan-Apr	Jan-Apr	Jan-Apr	95	[9, 37, 52- 55]
Clover	Oct- Dec	Oct- Dec	Oct- Dec	Oct- Dec	Oct-Dec	Oct-Dec	Oct- Dec	Oct-Dec	-	Oct-Dec	Oct-Dec	Jan-Mar	365 (perennial crops)	[9, 39, 53, 55].
Date	Oct-Jan	Aug-Jan	Oct- Jan	Oct- Jan	Aug-Jan	Aug-Jan	Oct-Jan	Oct-Jan	Oct- Jan	Oct-Jan	Aug-Jan	Oct-Mar		[9, 40, 53, 55-56].
Citrus	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Mar- Apr		[9, 53]
Grapes	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Mar-Apr	Mar- Apr	Mar-Apr	-	Mar-Apr	Mar-Apr	Mar-Apr		[9, 53, 57]

*The growing period for grapes was obtained from CROPWAT software [9].

3.3.4 Cultivated Area

The data of cultivated areas were obtained from the SSYB and MOA [10–11]. The data are presented in Table 3.9 for each type of crop in each region. Table 3.10 shows that the total cultivated area in the Kingdom was about 722 thousand hectares in 2009 without the green house cultivated lands. Riyadh region had the highest cultivated area (181,733 hectares) followed by Qaseem (97,408 hectares), Al-Jouf (92,006 hectares), Jazan (91,168 hectares), Hail (79,540 hectares) and Eastern region (55,083 hectares). Wheat had the largest cultivated area (195,884 hectares) followed by dates (161,963 hectares) and clover (102,100 hectares), indicating that these crops might have consumed more water than the other crops [10]. Further details of cultivated areas are presented in Table 3.10.

Table 3. 10: Cultivated area for each type of crop in each region in Saudi Arabia [10–11].

Crop	Cultivated Area in Each Region (hectares)												Total
	Riyadh	Makkah	Madinah	Qaseem	Eastern Region	Aseer	Tabouk	Hail	Jazan	Najran	Al-Baha	Al-Jouf	
Wheat	30896	371	194	22792	30691	3155	17889	23558	-	763	413	65162	195,884
Millet (Grains)	-	1255	2	-	-	78	-	-	2422	-	3	-	3,760
Sorghum	1037	5853	-	-	-	2173	-	-	83618	-	76	-	92,757
Maize	2212	619	1	5983	282	201	20	16967	935	-	99	2179	29,498
Barley	652	306	12	55	226	660	278	360	16	33	60	801	3,459
Tomato	4383	2041	1050	920	1605	1547	389	611	1221	540	108	693	15,108
Potato	3446	172	2	3826	135	67	2342	5800	-	32	6	1837	17,665
Other vegetables	40879	9080	983	6671	4926	1142	1082	3885	2486	927	251	1601	73,913
Clover	50090	638	2485	14786	2673	1419	9008	7127	-	1914	52	11908	102,100
Dates	43178	10771	18576	39303	13548	5075	2249	18743	288	3367	1395	5470	161,963
Citrus	3582	1711	755	2014	820	329	1868	1350	182	1833	43	727	15,214
Grapes	1378	727	3105	1058	177	434	1154	1139	-	41	194	1628	11,035
Total	181,733	33,544	27,165	97,408	55,083	16,280	36,279	79,540	91,168	9,450	2,700	92,006	722,356

3.4 CROPWAT Software and CLIMWAT Database

FAO has developed the CROPWAT software to estimate the CWR under various scenarios of climatic changes [50, 58]. Since the inception of the CROPWAT software system, it has been widely used in assessing CWR and scheduling agricultural crops in many parts of the world [58]. Smith and Kivumbi [58] conducted a study to assess the possibility of application of the CROPWAT software system for deficit irrigation scheduling on sugar beet, potatoes and cotton in Morocco, Pakistan and Turkey respectively. George et al. [59] developed an irrigation schedule model (ISM) for a single and multiple fields. The model was tested using field data and CROPWAT software outputs. The results were almost similar for the soil moisture, while some variation was observed for both the single and multiple-fields after second irrigations. Anadranistakis et al. [60] estimated CWR, where the model was validated using the experimental data for cotton, wheat and maize in Greece. Sheng-Feng et al. [61] used CROPWAT software to predict CWR in the ChiaNan irrigation district in Taiwan using the experimental data from Hsueh Chia station. The results demonstrated that the CROPWAT irrigation management model could be used to estimate the agricultural water requirements with different cropping patterns. Wahaj et al. [62] analyzed evapotranspiration of five commonly grown crops (maize, millet, sorghum, groundnuts and beans) in two selected districts in Africa. The results demonstrated that 2°C increase in temperature and doubling of CO_2 concentration in atmosphere might shorten the growing period of maize resulting in the decrease in CWR. The CROPWAT models were compared with the MODWht and CERES-Wheat models for winter wheat productions in Texas and Henan

[63]. These studies demonstrated that cumulative ET_o, predicted by CROPWAT, was better than the other models. Several other studies have used CROPWAT models and validated the models using experimental and satellite data [59-67]. These studies observed reasonable values of the CWR from the CROPWAT software system. These studies showed that the CROPWAT software system could be useful in improving the design of experimental methods. CLIMWAT database can be used in combination with CROPWAT software model to predict CWR [50]. CLIMWAT database includes the historical monthly average values of the climatic parameters for about thirty years from a total of 3262 meteorological stations in 144 countries, including Saudi Arabia [62]. Past studies have demonstrated that the CROPWAT software system can be used as a reliable tool to estimate CWR and irrigation scheduling. To understand the implication of climate change in Saudi Arabia, this study aims to use the CROPWAT software system.

3.5 Method for Calculating CWR

The CROPWAT software integrates several models necessary for predicting CWR, irrigation water management and crop scheduling [58]. It uses the FAO approved Penman-Monteith method to predict ET_o, ET_c and irrigation water management [50, 58]. It is to be noted that ET_c represents the amount of water that crops loss due to evapotranspiration while CWR represents the amount of water to be supplied [67]. The CWR was estimated for each crop and then added through the irrigation scheme to predict the total agricultural water requirements. The first step in the CROPWAT software is to predict ET_c on 10 day basis (e.g., time step = 10 days) as:

$$ET_c = ET_o \times K_c \tag{3.1}$$

Where, ET_c = actual evapotranspiration by the crop (mm/day), ET_o = reference evapotranspiration (mm/day); K_c = crop coefficient at a specific growth stage. K_c depends on the type of crop (e.g., height of crop, resistance of canopy, albedo), soil and climatic parameters, such as, soil surface and evaporation from soil [50, 58]. Albedo is the fraction of solar radiation reflected by the surface of crop and soil, whereas the canopy means the leaves and branches of crops that make a kind of roof in a crop. Resistance of canopy is the resistance of the crop against vapor transfer. It is affected by the area and the age of leaf [50]. The value of K_c varies over the growing period of the crop (e.g., initial stage, crop development, mid-season and late season). The change in K_c during different growth stages changes CWR for a crop [50, 58]. On the other hand, ET_o depends on climatic data (e.g., temperature; wind speed; sunshine period and humidity). The Penman-Monteith method has been recommended by FAO for its appropriate combinations of relevant climatic parameters for predicting ET_o [51, 58, 67].

The basic features of the Penman-Monteith method includes: (i) height of the reference grass of 0.12 m; (ii) surface resistance of 70 s/m; and (iii) albedo of 0.23. These assumptions represent evaporation from the surface of wide range of high standard green grass with enough water and active growth [50]. The Penman-Monteith method can be presented as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{3.2}$$

Where, ET_o = reference evapotranspiration (mm/day); R_n = net radiation at the crop surface in mega joules per square meter per day ($MJ/m^2/day$); G = soil heat flux density ($MJ/m^2/day$); T = mean daily air temperature at 2 m height (°C); u_2 = wind speed at 2 m height (m/s); e_s = saturation vapor pressure (kPa); e_a = actual vapor pressure (kPa); e_s-e_a = saturation vapor pressure deficit (kPa); Δ = slope of vapor pressure curve (kPa/°C); and γ = psychrometric constant (kPa/°C).

In assessing CWR for a crop, it is essential to understand the effective rainfall over the cultivated area. Using the historical data, effective rainfall can be calculated following Sheng-Feng et al. [61] and Molua and Lambi [68] as:

$$P_{eff} = P_{tot} \frac{125 - 0.2 P_{tot}}{125} \tag{3.3}$$

Where, P_{eff} = effective rainfall (mm) and P_{tot} = total rainfall (mm). Equation 3.3 is valid for a rainfall of $P_{tot} < 250$ mm. In Saudi Arabia, major parts of the country have average monthly rainfall less than this value [10]. The effective rainfall is used by the crop and thus the CWR is likely to be reduced by the similar amount. Following the prediction of CWR for each crop, the monthly agricultural water requirements for irrigation (IWR) can be predicted as:

$$Q = \sum_{i=1}^{n} A_i (ET_{c_i} - P_{eff}) \times 10^4 \qquad (3.4)$$

Where, Q = monthly agricultural water requirement of irrigation scheme (m^3/day); i = crop index; A_i = crop planted area (hectare); ET_{ci} = actual crop evapotranspiration (mm/day); P_{eff} = the effective rainfall (mm/day) and 10^4 is conversion factor from hectare to m^2 [61].

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 General

The analysis was performed for each region using the data of 2011 and the predicted data for 2050. The analysis predicted ET_o, P_{eff} and ET_c. The CWR for each crop were added following the irrigation scheme planning and the monthly agricultural water requirements were predicted. The total CWR were determined for each crop using the cultivated area in each region for the S1 – S4 scenarios. The CWR varies from region to region. The findings for the regions of Riyadh, Makkah, Madinah, Qaseem, Eastern Region, Aseer, Tabouk, Hail, Jazan, Najran, Al-Baha and Al-Jouf are summarized below.

4.2 Riyadh Region

4.2.1 Reference Evapotranspiration (ET_o)

The ET_o in the S1 – S4 scenarios are presented in Figure 4.1. It shows that the ET_o for S1 scenario varies in the range of 3.2 – 10.9 mm/day. ET_o increases gradually from 3.3 mm/day in Jan. to the peak value of about 10.9 mm/day in Jun., followed by a gradual decrease to 3.2 mm/day in Dec. The highest ET_o in Jun. can be explained by the hot and dry summer, low soil moisture and very small of rainfall in this month. The monthly variation of ET_o indicates that time of planting can affect the CWR significantly for a particular type of crop. In S2 scenario, minimum and maximum ET_o was predicted to be in the range of 3.4 - 11.4 mm/day. In Dec., ET_o was minimal (3.4 mm/day), while in Jun., it was maximum (11.4 mm/day). It increases gradually from about 3.5 mm/day in Jan. to the peak value of about 11.4 mm/day in Jun. Then it decreases gradually to 3.4 mm/day in Dec. Comparison between S1 and S2 shows that ET_o increases from 10.9 to 11.4 mm/day in Jun. from 2011 to 2050. The yearly average of ET_o was 6.9 mm/day in 2011, which was predicted to be 7.3 mm/day in 2050 (5.4% increase). The S3 and S4 scenarios are almost similar to the S1 and S2 scenarios, respectively.

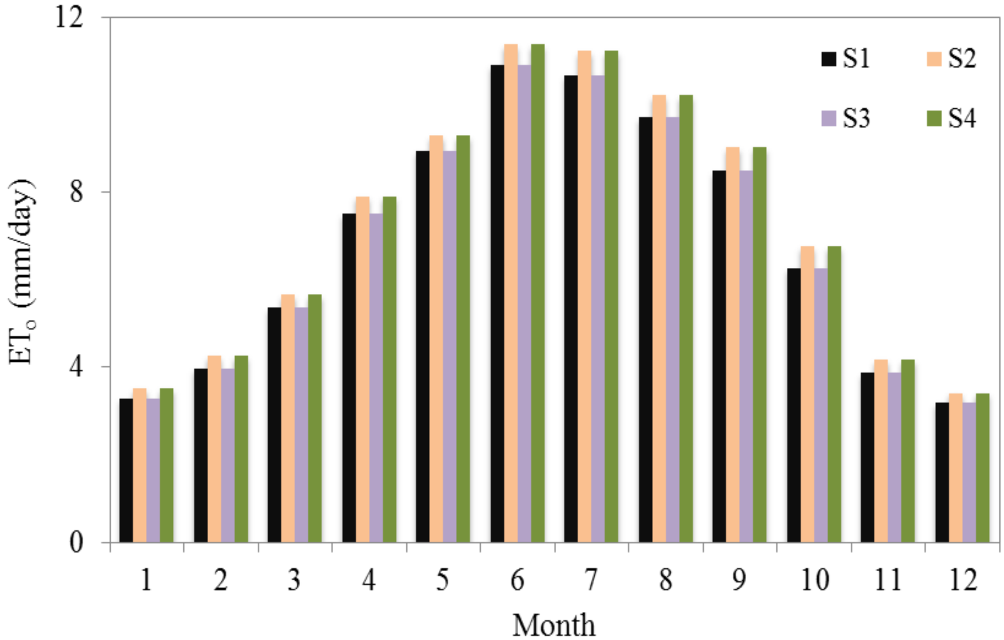

Figure 4.1: Change in ET_o from 2011 to 2050 for Riyadh region

[1-12: Jan-Dec.]

4.2.2 Effective Rainfall (P_{eff})

The effective rainfall showed considerable monthly variation (Table 4.1). In the S1 and S2 scenarios, the maximum effective rainfall was 28 mm/month in Apr. and between 0.1 - 23.1 mm/month in the other months. The total annual effective rainfall was estimated to be 98.3 mm. The annual effective rainfall in 2050 has been predicted to be approximately 106.6 mm/yr. In the S3 and S4 scenarios, the maximum predicted effective rainfall is approximately 26.6 mm/month in Apr.

Table 4. 1: Effective rainfall in Riyadh region for S1 - S4 scenarios

Scenarios	Effective Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
S1 and S2	11.1	9.9	23.1	28.0	7.7	0.1	0.4	0.6	0.1	1.2	5.5	10.5	98.3
S3 and S4	15.6	3.9	18.8	26.6	8.1	0.0	0.0	4.2	12.9	1.7	3.4	11.5	106.6

4.2.3 Crop Water Requirement (CWR)

This study predicted approximately 2803, 2951, 2797 and 2945 MCM/yr of total CWR for S1, S2, S3 and S4 scenarios respectively. The S2 and S4 scenarios will require approximately 143-148 MCM/yr of additional water than the S1 scenario. The increase in CWR in S2 and S4 scenarios were due to the increase in temperature mainly. The effects of rainfall changes were predicted to be minimal (S3 scenario), possibly, due to insignificant change in the rainfall in this region.

The CWR for winter wheat were predicted to be 200, 211, 203 and 214 MCM/yr for S1, S2, S3 and S4 scenarios respectively (Tables A.1). Increase in CWR for wheat from 2011 to 2050 is expected to be 11-14 MCM/yr (Figure 4.2). The CWR for vegetables was approximately 465, 486, 465 and 486 MCM/yr for S1 - S4 scenarios respectively. Increase in CWR for vegetables is approximately 21 MCM/yr from 2011 to 2050. The CWR for fodder crop was predicted to be 989, 1042, 985 and 1038 MCM/yr for the S1 - S4 scenarios respectively. Increase in CWR for the fodder crop was approximately 53 MCM/yr from 2011 to 2050. CWR for dates was approximately 1032, 1088, 1028 and 1085 MCM/yr for S1 - S4 scenarios. The increase in CWR for dates is 56 MCM/yr from 2011 to 2050. The results indicate that dates, clover, wheat and vegetables consumed approximately 36.8, 35.3, 7.1 and 16.6% of CWR respectively. The other crops (e.g., sorghum, maize, barley, grapes and citrus) also need 2 - 65 MCM/yr of water, representing to about 4.2% of the estimated CWR (Figure 4.3).

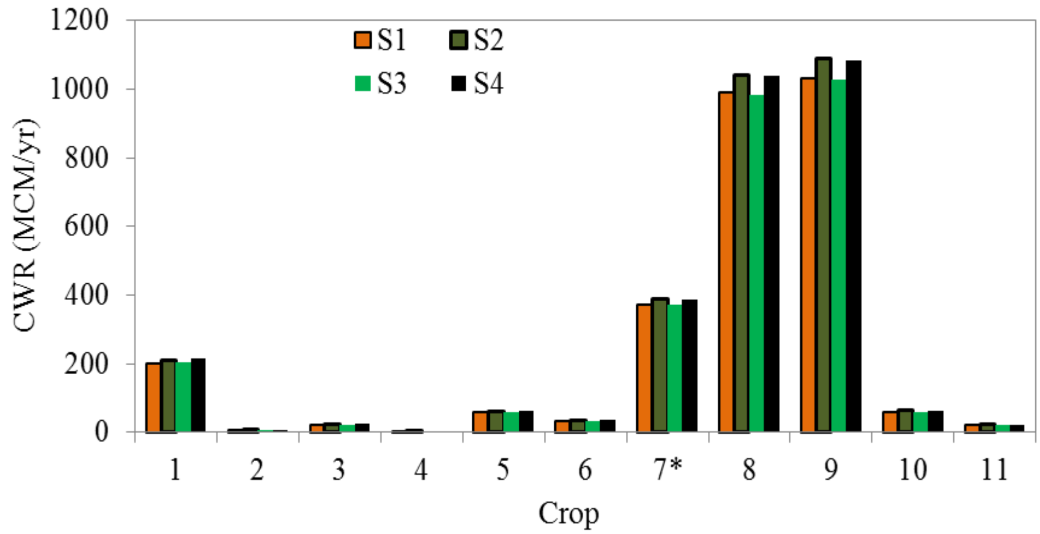

Figure 4.2: CWR for crops in Riyadh region

[1: wheat, 2: sorghum, 3: maize, 4: barley, 5: tomato, 6: Potato, 7: other vegetables, 8: clover, 9: dates, 10: citrus and 11: grapes]; *[marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon].

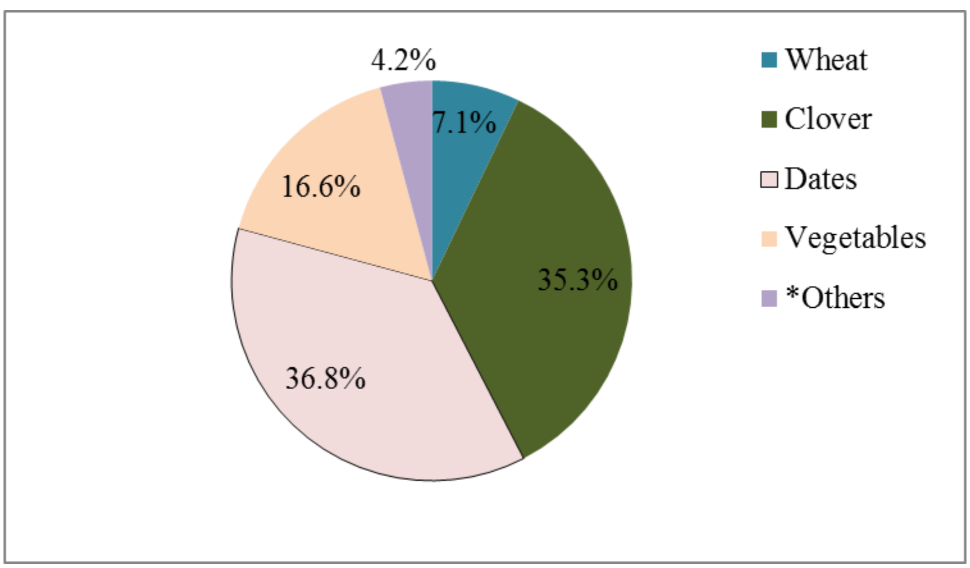

Figure 4.3: Percentage of CWR for some crops in Riyadh region

*[sorghum: 0.3%; maize: 0.9%; barley: 0.08%; citrus: 2.2%; grapes: 0.8%]

4.3 Makkah Region

4.3.1 Reference Evapotranspiration (ET_o)

The ET_o for the S1 – S4 scenarios are presented in Figure 4.4. The ET_o increases steadily from approximately 4.6 mm/day in Jan. to the peak value of about 7.6 mm/day in Jul., followed by a steady decrease to 4.5 mm/day in Dec. The highest ET_o are in the range of 7.5 – 7.6 mm/day in Jun. - Aug., which can be explained by the hot and dry summer and low rainfall in these months. In S2 scenario, minimum and maximum ET_o was predicted in the range of 4.8 – 8.1 mm/day. In Dec., ET_o was lowest (4.8 mm/day), while in Jul., it was highest (8.1 mm/day). It increases gradually from about 5 mm/day in Jan. to the peak value of about 8.1 mm/day in Jul. Then it decreases to 4.8 mm/day in Dec. ET_o increases from 7.6 to 8.1 mm/day in Jul. for the S1 and S2 scenarios from 2011 to 2050. Average annual ET_o was 6.1 mm/day in 2011, which was predicted to be 6.5 mm/day in 2050 (6.9% increase).

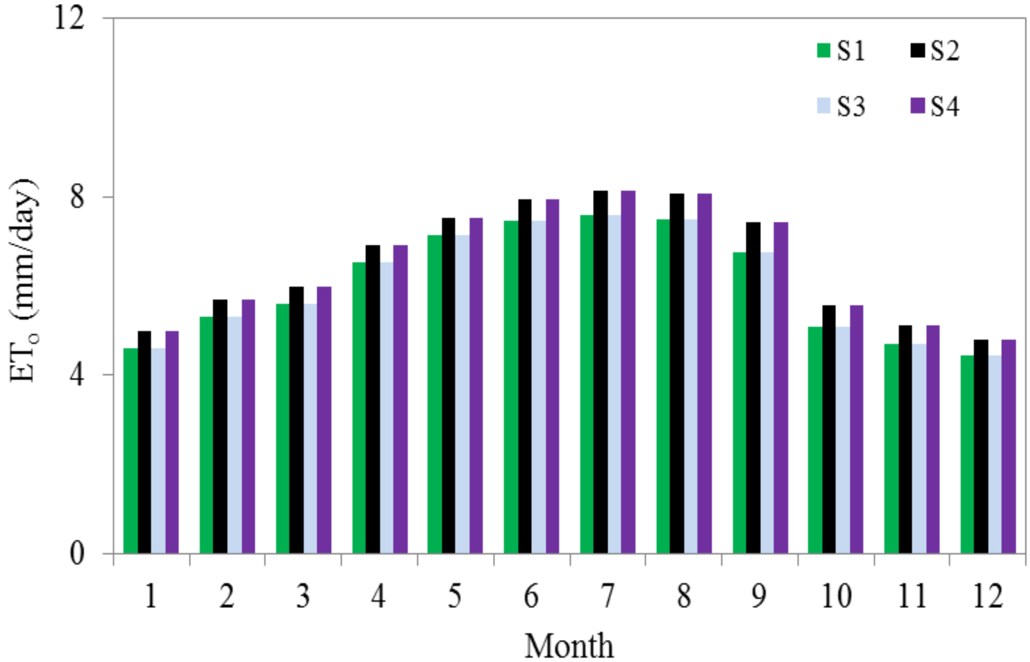

Figure 4.4: Change in ET$_o$ from 2011 to 2050 for Makkah region

[1-12: Jan.-Dec.]

4.3.2 Effective Rainfall (P_{eff})

The effective rainfall showed considerable monthly variation (Table 4.2). In the S1 and S2 scenarios, maximum effective rainfall was 17.5 mm/month in Nov., whereas it was zero in Jun. - Sep. and between 01 - 16.5 mm/month in the other months. The total annual effective rainfall was estimated to be 57.7 mm. The annual effective rainfall in 2050 has been predicted to be approximately 89.3 mm/yr. In the S3 and S4 scenarios, the maximum predicted effective rainfall does not exceed 18.1 mm/month in Dec. The effective rainfall projected to increase from 57.7 to 89.3 from 2011 to 2050 (Table 4.2).

Table 4. 2: Effective rainfall in Makkah region for S1 - S4 scenarios

Scenario	Effective Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
S1 and S2	11.8	5.0	3.0	2.0	1.0	0.0	0.0	0.0	0.0	1.0	17.5	16.5	57.7
S3 and S4	17.7	6.9	3.4	1.9	0.5	0.0	0.0	5.6	10.6	6.8	17.7	18.1	89.3

4.3.3 Crop Water Requirement (CWR)

This study estimated approximately 402, 431, 398 and 426 MCM/yr of total CWR for S1, S2, S3 and S4 scenarios respectively. The S2 and S4 scenarios will require approximately 24-29 MCM/yr of additional water than the S1 scenario. The effects of rainfall changes were predicted to be minimal (S3 scenario).

The CWR for sorghum was expected to be 36 - 38 MCM/yr for S1-S4 scenarios respectively (Figure 4.5). Increase in CWR for sorghum from 2011 to 2050 is approximately 2 MCM/yr. The CWR for winter wheat was predicted to be approximately 2.6, 2.7, 2.5 and 2.7 MCM/yr for S1, S2, S3 and S4 scenarios respectively (Tables A.2). Increase in CWR for wheat from 2011 to 2050 is approximately 0.1 MCM/yr (Figure 4.5). The CWR for vegetables was approximately 80 - 86 MCM/yr for S1 - S4 scenarios. Increase in CWR for vegetables is approximately 6 MCM/yr from 2011 to 2050. The CWR for fodder crop was predicted to be 10 - 11 MCM/yr for the S1 - S4 scenarios. Increase in CWR for the fodder crop was approximately 1 MCM/yr from 2011 to 2050. CWR for dates was approximately 226, 242, 222 and 239 MCM/yr for S1 - S4 scenarios. The increase in CWR for dates is 16 MCM/yr from 2011 to 2050. The results indicate that dates, vegetables and sorghum consumed approximately 56.1, 20 and 8.9% of CWR respectively. The other crops (e.g., wheat, millet, maize, barley, clover, citrus and grapes) need 1 - 28 MCM/yr of water, representing about 15% of the estimated CWR (Tables A.2 and Figure 4.6).

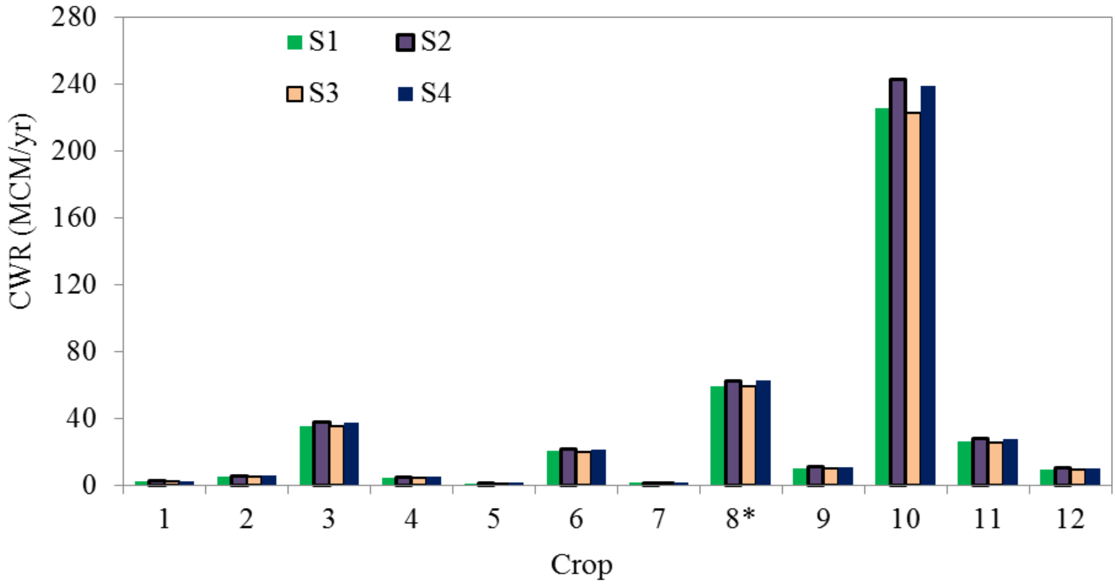

Figure 4.5: CWR for crops in Makkah region.

[1: wheat, 2: millet, 3: sorghum, 4: maize, 5: barley, 6: tomato, 7: Potato, 8: other vegetables, 9: clover, 10: dates, 11: citrus and 12: grapes]; *[marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon]

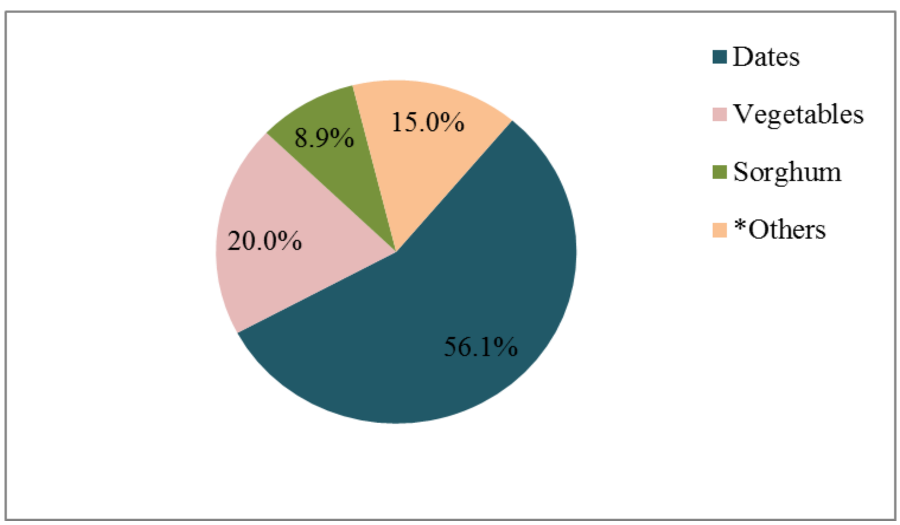

Figure 4.6: Percentage of CWR for some crops in Makkah region

*[wheat: 0.7%; millet: 1.3%; maize: 1.2%; barley: 0.3%; clover: 2.6%; citrus: 6.5%; grapes: 2.4%]

4.4 Madinah Region

4.4.1 Reference Evapotranspiration (ET_o)

The ET_o for the S1 – S4 scenarios are presented in Figure 4.7. Figure 4.7 shows that ET_o in 2011 (S1 scenario) varies in the range of 3.5 – 9.6 mm/day. The yearly average of ET_o was 6.7 mm/day in 2011, which was predicted to be 7.1 mm/day in 2050 (5% increase). The results indicate that CWR may be the highest during May - Aug. and lowest during Dec. – Feb. (Figure 4.7).

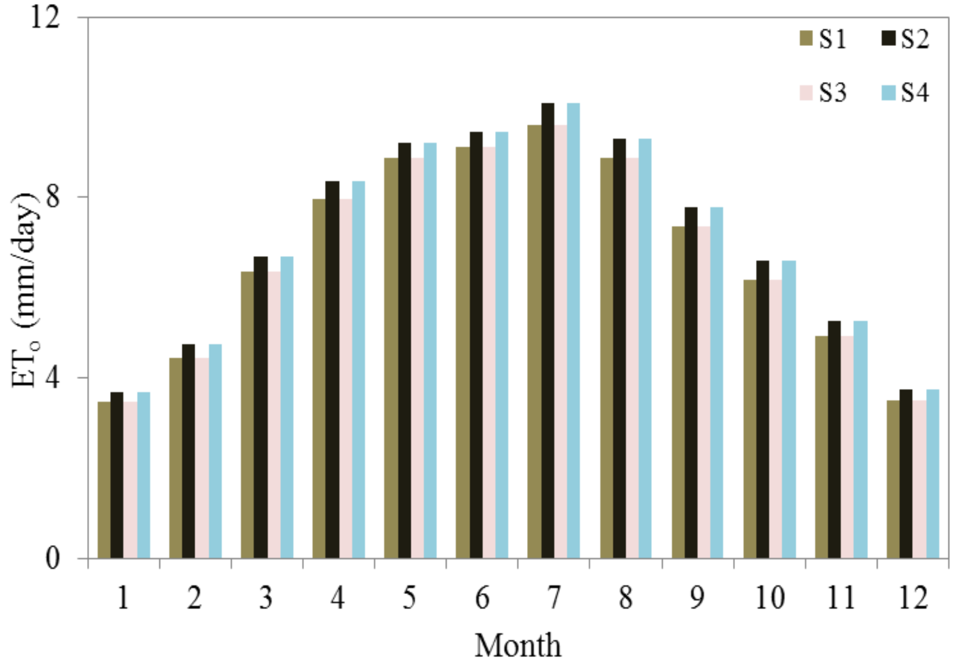

Figure 4.7: Change in ET$_o$ from 2011 to 2050 for Madinah region

[1-12: Jan.-Dec.]

4.4.2 Effective Rainfall (P_{eff})

In the S1 and S2 scenarios, maximum effective rainfall was 11.7 mm/month in Apr., whereas it was very small in Jun. - Sep. (0.1 – 0.4) and between 1.1 - 9.1 mm/month in the other months. The total annual effective rainfall was estimated to be 48.5 mm. The annual effective rainfall in 2050 has been predicted to be approximately 62.7 mm/yr. In the S3 and S4 scenarios, the maximum predicted effective rainfall is about 13.2 mm/month in Jan. It is predicted to be zero in (Feb., Jun. and Jul.) and between 1.5 - 12 mm/month in the other months in 2050. The effective rainfall projected to increase from 48.5 to 62.7 from 2011 to 2050 (Table 4.3).

Table 4. 3: Effective rainfall in Madinah region for S1 - S4 scenarios

Scenario	Effective Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
S1 and S2	7.9	1.2	8.2	11.7	4.6	0.4	0.2	0.3	0.1	1.1	9.1	3.8	48.5
S3 and S4	13.2	0.0	4.9	10.1	4.7	0.0	0.0	3.7	12.0	1.5	7.4	5.3	62.7

4.4.3 Crop Water Requirement (CWR)

The total CWR was predicted to be approximately 558, 586, 554 and 582 MCM/yr for S1, S2, S3 and S4 scenarios respectively. The S2 and S4 scenarios will require approximately 24-28 MCM/yr of additional water than the S1 scenario. The increase in CWR in S2 and S4 scenarios were due to the increase in temperature mainly. The effects of rainfall changes were predicted to be minimal (S3 scenario).

The CWR for winter wheat was predicted to be approximately 1.4 - 1.5 MCM/yr for S1 – S4 scenarios (Tables A.3). Increase in CWR for wheat from 2011 to 2050 is approximately 0.1 MCM/yr. CWR for other cereal crops (e.g., millet, maize and barley) are not significant. The CWR for vegetables was approximately 20-21 MCM/yr for S1 - S4 scenarios respectively. Increase in CWR for vegetables is approximately 1 MCM/yr from 2011 to 2050. The CWR for fodder crop was predicted to be 47, 49, 46 and 49 MCM/yr for the S1 - S4 scenarios respectively. Increase in CWR for the fodder crop was approximately 2 MCM/yr from 2011 to 2050. CWR for dates was approximately 429, 451, 426 and 448 MCM/yr for S1 - S4 scenarios. The increase in CWR for dates is 22 MCM/yr from 2011 to 2050. CWR for grapes was approximately 48, 50, 48 and 50 MCM/yr for S1 - S4 scenarios. The increase in CWR for grapes is 2 MCM/yr from 2011 to 2050. The results indicate that dates, grapes and clover consumed approximately 76.8, 8.6 and 8.4% of CWR respectively. The other crops (e.g., wheat, millet, maize, barley, vegetables and citrus) need about 0.01 - 20 MCM/yr of water representing about 6.2% of the estimated CWR (Figure 4.9).

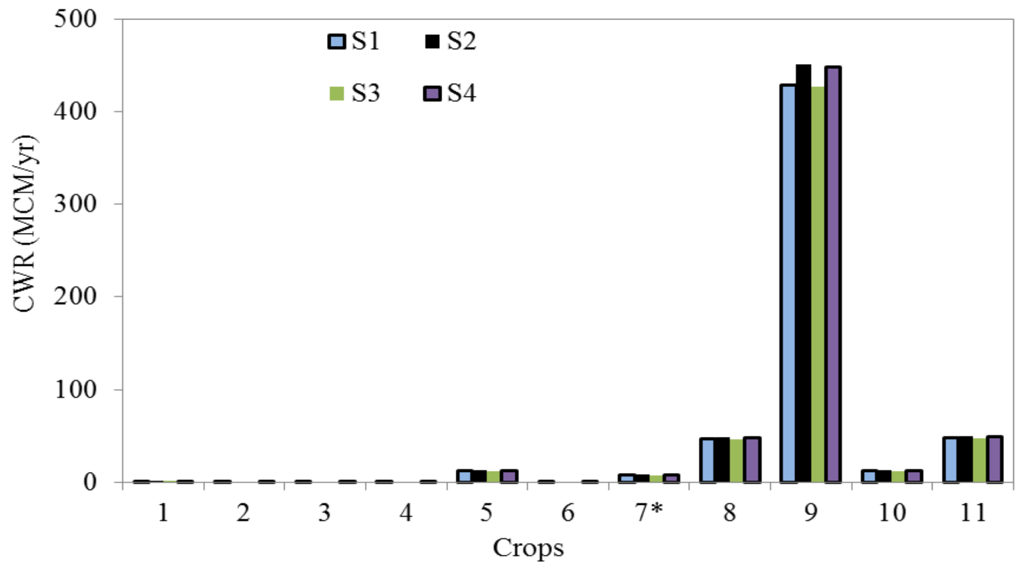

Figure 4.8: CWR for crops in Madinah region

[1: wheat, 2: millet, 3: maize, 4: barley, 5: tomato, 6: Potato, 7: other vegetables, 8: clover, 9: dates, 10: citrus and 11: grapes]; *[marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon]

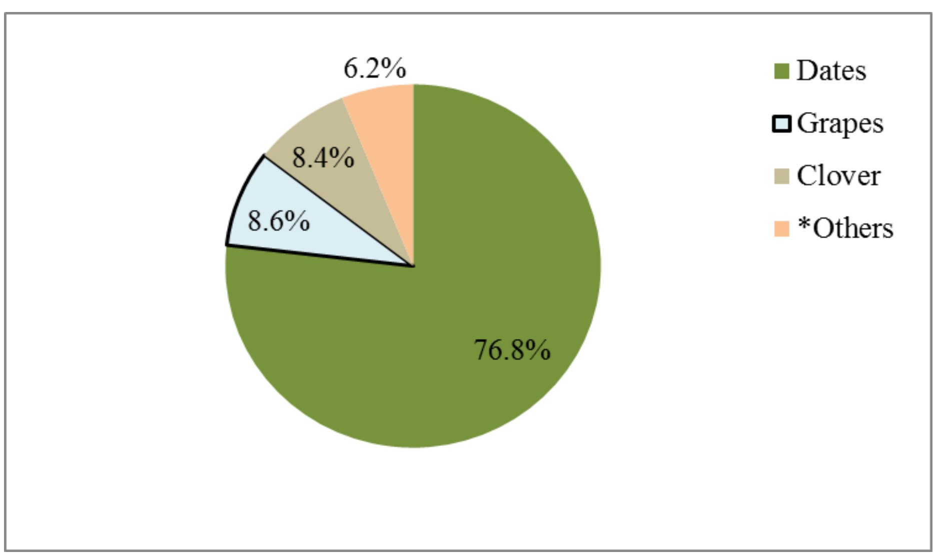

Figure 4.9: Percentage of CWR for some crops in Madinah region

*[wheat: 0.3%; vegetables: 3.6%; citrus: 2.3%]

4.5 Qaseem Region

4.5.1 Reference Evapotranspiration (ET_o)

The ET_o increases steadily from approximately 2.8 mm/day in Jan. to the peak value of about 9.6 mm/day in Jul. Then it decreases gradually to 3 mm/day in Dec. (Figure 4.10). The maximum ET_o increases from 9.6 to 10.1 mm/day in Jul. for the S1 and S2 scenarios from 2011 to 2050. The average annual ET_o was 6.3 mm/day in 2011, which was predicted to be 6.7 mm/day in 2050 (5.4% increase). Figure 4.10 shows also the results for the S3 and S4 scenarios, which are similar to the S1 and S2 scenarios respectively.

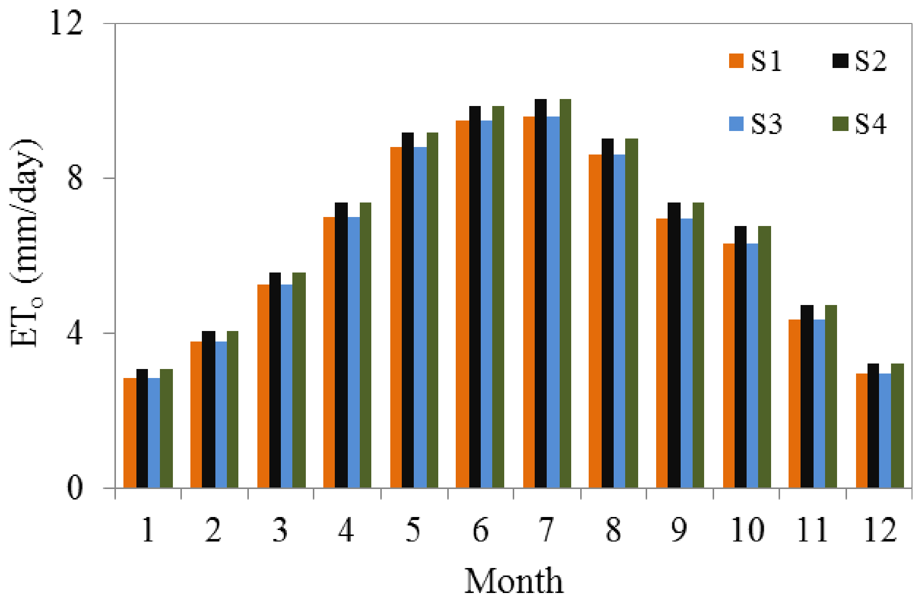

Figure 4.10: Change in ET$_o$ from 2011 to 2050 for Qaseem region

[1-12: Jan.-Dec.]

4.5.2 Effective Rainfall (P_{eff})

The effective rainfall showed significant monthly variation (Table 4.4). In the S1 and S2 scenarios, the maximum effective rainfall was 53.4 mm/month in Mar., whereas it was zero in Jun. - Sep. and between 4 – 34.8 mm/month in the other months. The total annual effective rainfall was estimated to be 172.3 mm. The annual effective rainfall in 2050 has been predicted to be approximately 192.5 mm/yr. In the S3 and S4 scenarios, the maximum predicted effective rainfall is about 53.6 mm/month in Mar. It is predicted to be zero in Jun. – Jul. and between 1.4 – 33.8 mm/month in the other months.

Table 4. 4: Effective rainfall in Qaseem region for S1 - S4 scenarios

Scenario	Effective Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
S1 and S2	17.5	9.8	53.4	34.8	4.0	0.0	0.0	0.0	0.0	4.0	19.4	29.5	172.3
S3 and S4	29.3	12.9	53.6	31.3	2.2	0.0	0.0	1.4	3.0	3.9	21.1	33.8	192.5

4.5.3 Crop Water Requirement (CWR)

The total CWR for Qaseem region was predicted to be approximately 1426, 1505, 1413 and 1494 MCM/yr for S1, S2, S3 and S4 scenarios respectively. The S2 and S4 scenarios will require approximately 68-79 MCM/yr of additional water than the S1 scenario. The increase in CWR in S2 and S4 scenarios were due to the increase in temperature mainly.

The CWR for winter wheat was predicted to be approximately 132, 140, 131 and 140 MCM/yr for S1, S2, S3 and S4 scenarios respectively (Tables A.4). Increase in CWR for wheat from 2011 to 2050 is approximately 8 MCM/yr. The CWR for vegetables was approximately 100-105MCM/yr for S1 - S4 scenarios respectively. Increase in CWR for vegetables is approximately 5 MCM/yr from 2011 to 2050. The CWR for fodder crop was predicted to be 252, 267, 250 and 264 MCM/yr for the S1 - S4 scenarios respectively. Increase in CWR for the fodder crop was approximately 15 MCM/yr from 2011 to 2050. CWR for dates was approximately 837, 886, 830 and 878 MCM/yr for S1 - S4 scenarios. Increase in CWR for dates is 49 MCM/yr from 2011 to 2050. The results indicate that dates, wheat, clover and vegetables consumed approximately 58.7, 9.2, 17.7 and 7% of CWR respectively (Figure 4.12). The other crops (e.g., maize, barley, grapes and citrus) needed 0.14 – 58 MCM/yr of water, representing about 7.4% of the estimated CWR.

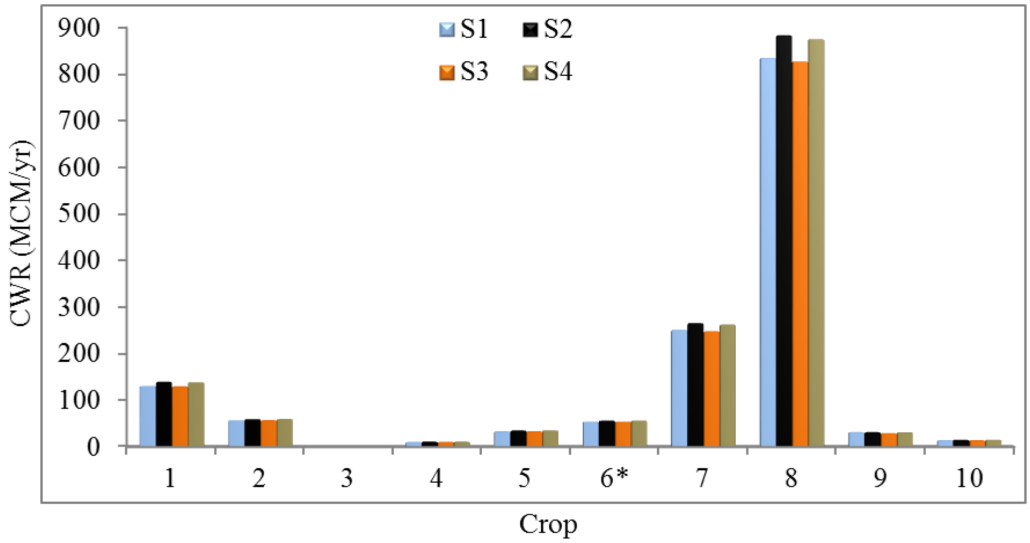

Figure 4.11: CWR for crops in Qaseem region.

[1: wheat, 2: maize, 3: barley, 4: tomato, 5: Potato, 6: other vegetables, 7: clover, 8: dates, 9: citrus and 10: grapes]; *[marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon]

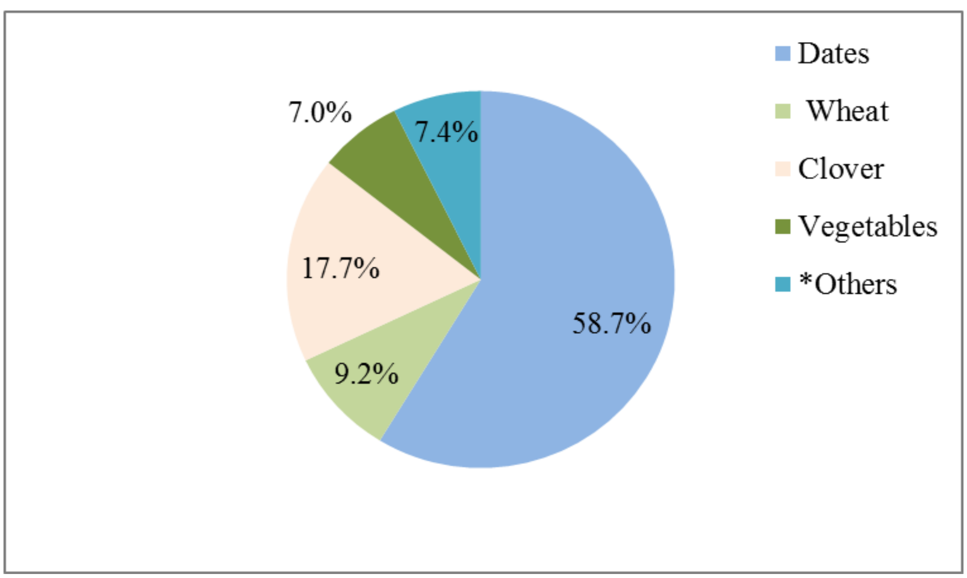

Figure 4.12: Percentage of CWR for some crops in Qaseem region

*[maize: 4%; barley: 0.01%; grapes: 1.04%; citrus: 2.3%]

4.6 Eastern Region

4.6.1 Reference Evapotranspiration (ET_o)

The ET_o for the S1 - S4 scenarios are presented in Figure 4.13. The ET_o increases gradually from approximately 2.2 mm/day in Jan. to the peak value of about 8.7 mm/day in Jul. Then it decreases gradually to 2.5 mm/day in Dec. The ET_o increases from 8.7 to 9.2 mm/day in Jul. for the S1 and S2 scenarios from 2011 to 2050, respectively. The average annual ET_o was 5.5 mm/day in 2011, which was predicted to be 5.8 mm/day in 2050 (6% increase).

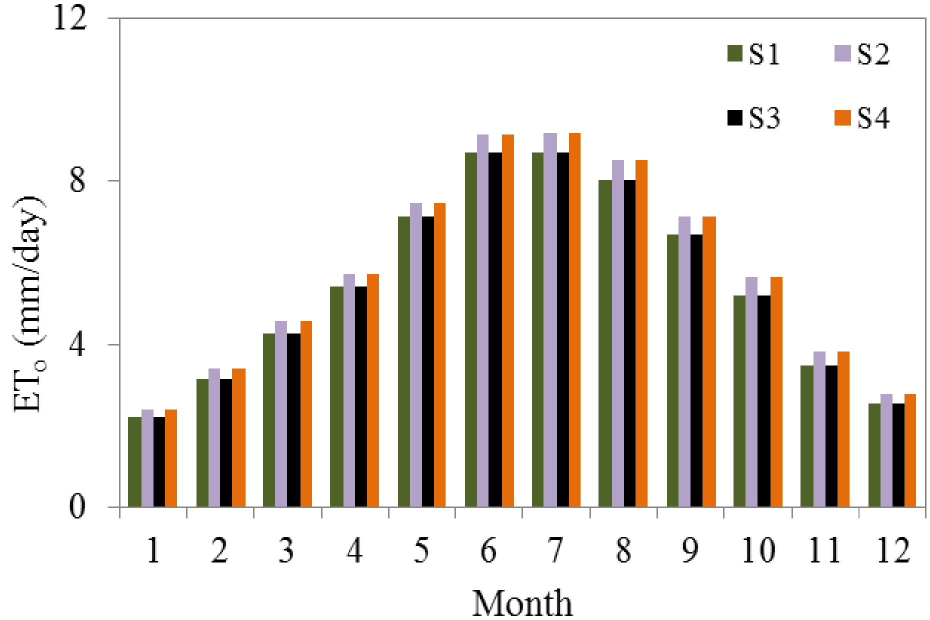

Figure 4.13: Change in ET_o from 2011 to 2050 for Eastern region

[1-12: Jan.-Dec.]

4.6.2 Effective Rainfall (P_{eff})

In the S1 and S2 scenarios, the maximum effective rainfall was 35.5 mm/month in Mar., whereas it was zero in Jun. – Jul. and Sep. and between 1.3 - 24.4 mm/month in the other months (Table 4.5). The total annual effective rainfall was estimated to be 155.5 mm for the S1-S2 scenarios. The annual effective rainfall in 2050 has been predicted to be approximately 176.3 mm/yr. In the S3 and S4 scenarios, the maximum predicted effective rainfall is about 36 mm/month in Mar. and Jan. In Jun. – Jul., the effective rainfall is expected to be zero, whereas it ranges between 2.3 and 29.3 in the other months.

Table 4. 5: Effective rainfall in Eastern region for S1 - S4 scenarios

Scenario	Effective Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
S1 and S2	24.1	24.4	35.5	16.3	8.7	0.0	0.0	1.3	0.0	4.8	21.4	19.0	155.5
S3 and S4	36.0	29.3	35.9	11.8	7.3	0.0	0.0	2.5	2.3	4.8	23.1	23.4	176.3

4.6.3 Crop Water Requirement (CWR)

The total CWR was predicted to be approximately 485, 517, 480 and 512 MCM/yr for S1, S2, S3 and S4 scenarios respectively. The S2 and S4 scenarios will require approximately 27-32 MCM/yr of additional water than the S1 scenario. The increase in CWR in S2 and S4 scenarios were due to the increase in temperature mainly.

The CWR for winter wheat was predicted to be 135, 145, 134 and 143 MCM/yr for S1, S2, S3 and S4 scenarios respectively (Tables A.5). The findings indicate that the effects of changes in temperature were significant. Increase in CWR for wheat from 2011 to 2050 is approximately 8-10 MCM/yr (Figure 4.14). The CWR for vegetables was approximately 53 - 56 MCM/yr for S1 - S4 scenarios respectively. Increase in CWR for vegetables is approximately 3 MCM/yr from 2011 to 2050. The CWR for fodder crop was predicted to be 39 - 41 MCM/yr for the S1 - S4 scenarios respectively. Increase in CWR for the fodder crop was approximately 2 MCM/yr from 2011 to 2050. CWR for dates was approximately 242, 258, 240 and 256 MCM/yr for S1 - S4 scenarios. The results indicate that dates, wheat, clover and vegetables consumed approximately 50, 27.9, 8 and 11% of CWR respectively (Figure 4.15). The other crops (e.g., maize, barley, citrus and grapes) needed 0.41 - 10 MCM/yr of water, representing about 3.1% of the estimated CWR.

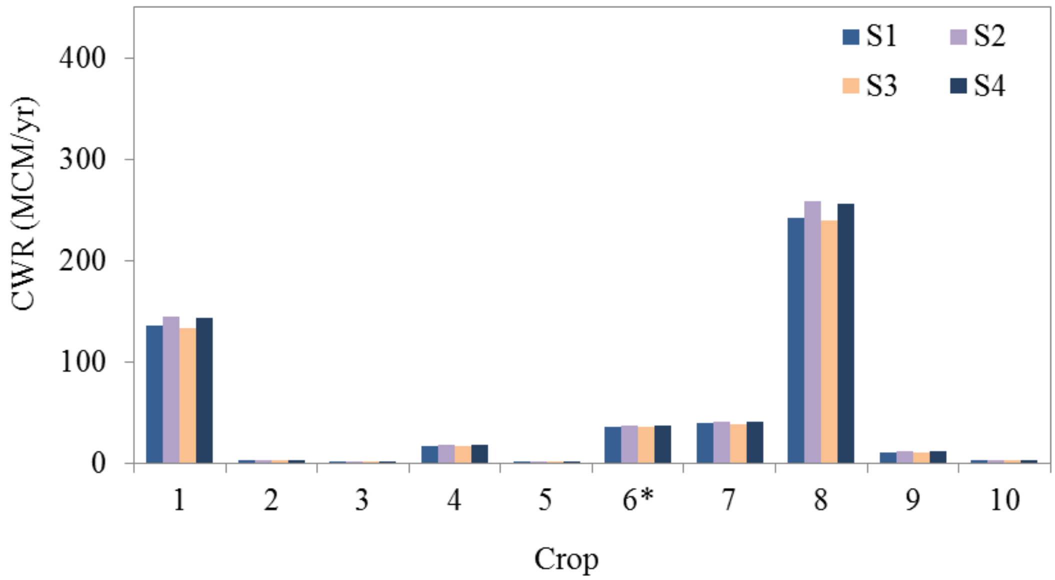

Figure 4.14: CWR for crops in Eastern region.

[1: wheat, 2: maize, 3: barley, 4: tomato, 5: Potato, 6: other vegetables, 7: clover, 8: dates, 9: citrus and 10: grapes]; *[marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon]

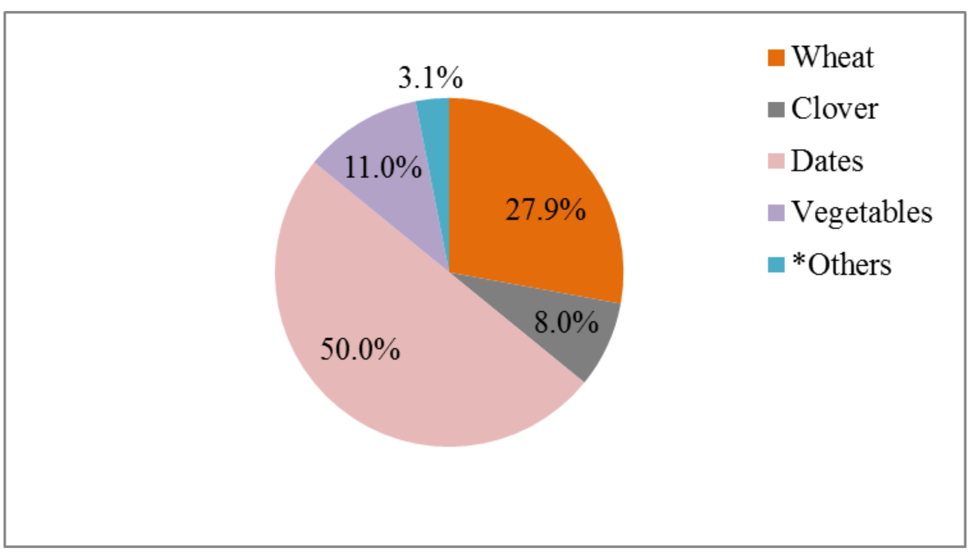

Figure 4.15: Percentage of CWR for some crops in Eastern region

*[maize: 0.5%; barley: 0.1%; grapes: 0.4%; citrus: 2.1%]

4.7 Aseer Region

4.7.1 Reference Evapotranspiration (ET_o)

The ET_o fluctuates throughout the year. The ET_o increases steadily from approximately 3.5 mm/day in Jan. to about 6.2 mm/day in Jun. Then it decreases to 5.6 mm/day in Aug. and increases again to 6.3 in Sep. and then finally decreases to 3.2 in Dec. The small change in ET_o in the range of 3.5 – 6.3 mm/day during the winter and summer seasons can be explained by the low temperature variability and higher rainfall. In S2 scenario, minimum and maximum ET_o was predicted to be in the range of 3.5 – 6.8 mm/day. In Dec., ET_o was minimal (3.5 mm/day), while in Jul and Sep., it was maximum (6.5 – 6.8 mm/day). The average annual ET_o was 5 mm/day in 2011, which was predicted to be 5.3 mm/day in 2050 (6% increase).

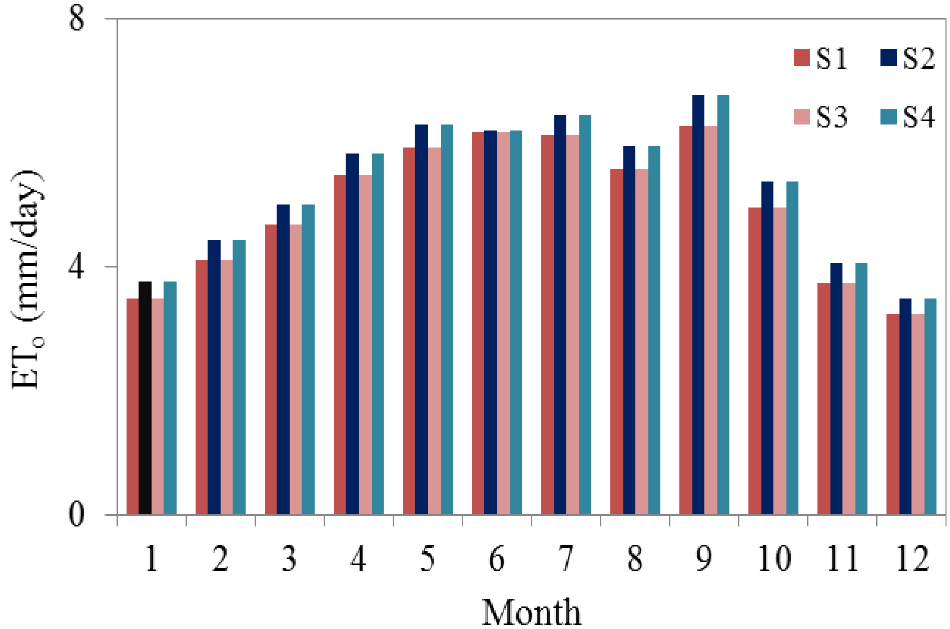

Figure 4.16: Change in ET_o from 2011 to 2050 for Aseer region

[1-12: Jan.-Dec.]

4.7.2 Effective Rainfall (P_{eff})

The effective rainfall in Aseer region is much higher comparing to the other regions (Table 4.6). The maximum effective rainfall reached to 60.6 mm/month in Mar. for the S1 and S2 scenarios, whereas it was between 3 - 48.5 mm/month in the other months. The total annual effective rainfall was estimated to be 246.8 mm. The annual effective rainfall in 2050 has been predicted to be approximately 299.3 mm/yr. In the S3 and S4 scenarios, the maximum predicted effective rainfall is about 55.4 mm/month in Mar., while the minimum is about 5.1 in Jun.

Table 4. 6: Effective rainfall in Aseer region for S1 - S4 scenarios

Scenario	Effective Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
S1 and S2	7.9	10.8	60.6	48.5	34.8	5.9	24.0	28.6	5.9	3.0	10.8	5.9	246.8
S3 and S4	12.9	16.0	55.4	49.1	33.8	5.1	21.9	36.7	24.4	21.6	11.3	11.2	299.3

4.7.3 Crop Water Requirement (CWR)

This study predicted approximately 146, 155, 141 and 151 MCM/yr of total CWR in Aseer region for S1, S2, S3 and S4 scenarios respectively. The S2 and S4 scenarios will require approximately 5-9 MCM/yr of additional water than the S1 scenario. The CWR for wheat is highest, followed by sorghum, barley, maize and millet (Table A.6 and Figure 4.17). The CWR for winter wheat were predicted to be approximately 14 - 15 MCM/yr for S1 - S4 scenarios, while the CWR for sorghum was predicted to be 10 - 11 MCM/yr for S1 - S4 scenarios. The findings indicate that the effects of temperature and rainfall changes from 2011 to 2050 may not affect the CWR significantly. The CWR for vegetables was approximately 17-18 MCM/yr for S1 - S4 scenarios respectively. Increase in CWR for vegetables is approximately 1 MCM/yr from 2011 to 2050. The CWR for fodder crop was predicted to be 16-17 MCM/yr for the S1 - S4 scenarios respectively. Increase in CWR for the fodder crop was approximately 1 MCM/yr from 2011 to 2050. CWR for dates was approximately 78-83 MCM/yr for S1 - S4 scenarios, representing 5 MCM/yr of CWR increase from 2011 to 2050. The results indicate that dates, wheat, clover, sorghum and vegetables consumed approximately 53.3, 9.3, 11.2, 7 and 11.7% of CWR respectively; while the remaining is consumed by the other crops (Figure 4.18).

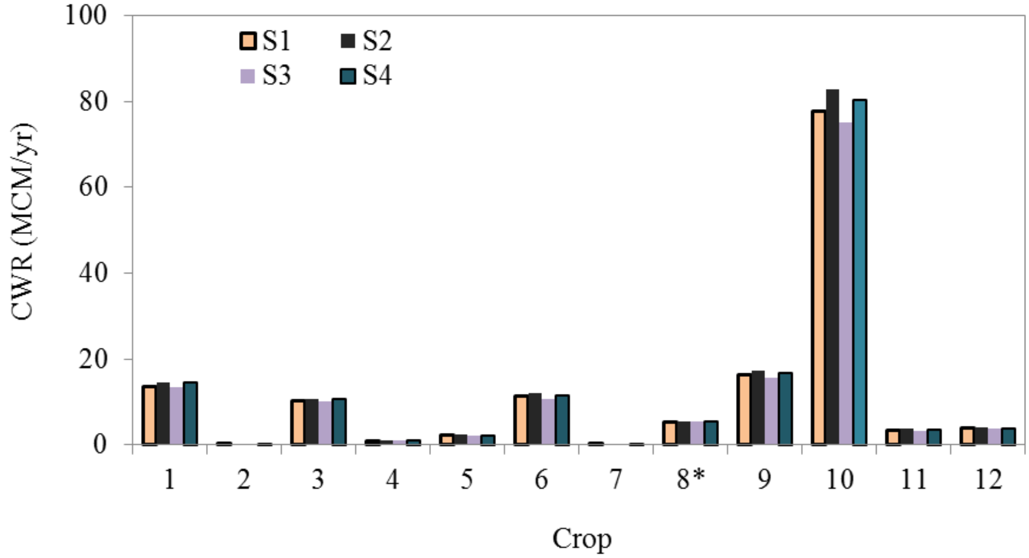

Figure 4.17: CWR for crops in Aseer region.

[1: wheat, 2: millet, 3: sorghum, 4: maize, 5: barley, 6: tomato, 7: Potato, 8: other vegetables, 9: clover, 10: dates, 11: citrus and 12: grapes]; *[marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon

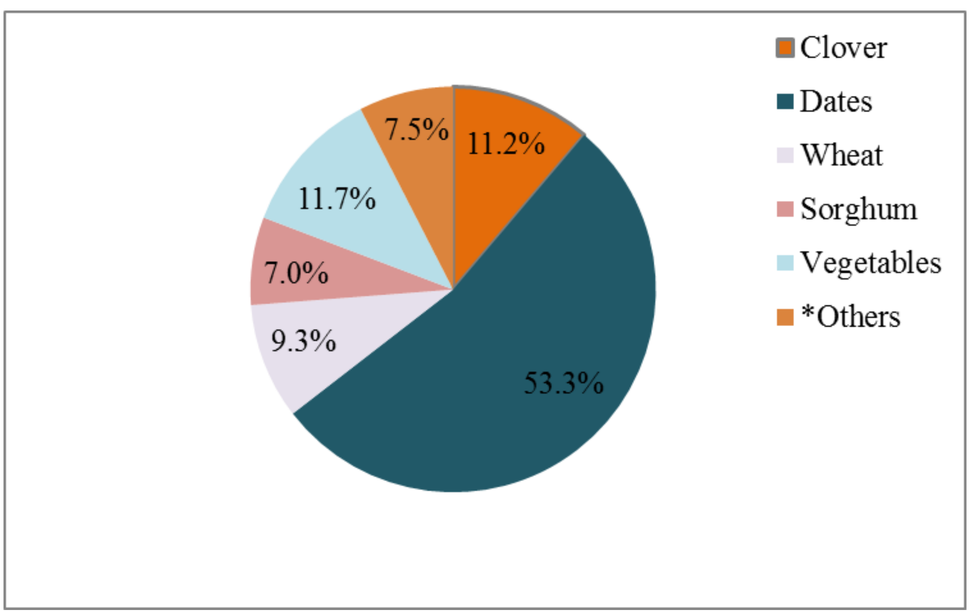

Figure 4.18: Percentage of CWR for some crops in Aseer region

*[millet: 0.1%; maize: 0.7%; barley: 1.5%; citrus: 2.4%; grapes: 2.8%]

4.8 Tabouk Region

4.8.1 Reference Evapotranspiration (ET_o)

The ET_o increases steadily from approximately 2.8 mm/day in Jan. to the peak value of about 8.6 mm/day in Jul. Then it decreases gradually to 2.5 mm/day in Dec. (Figure 4.19). In S2 scenario, similar variability was observed. The average of annual ET_o was 5.8 mm/day in 2011, which was predicted to be 6.2 mm/day in 2050 (6% increase).

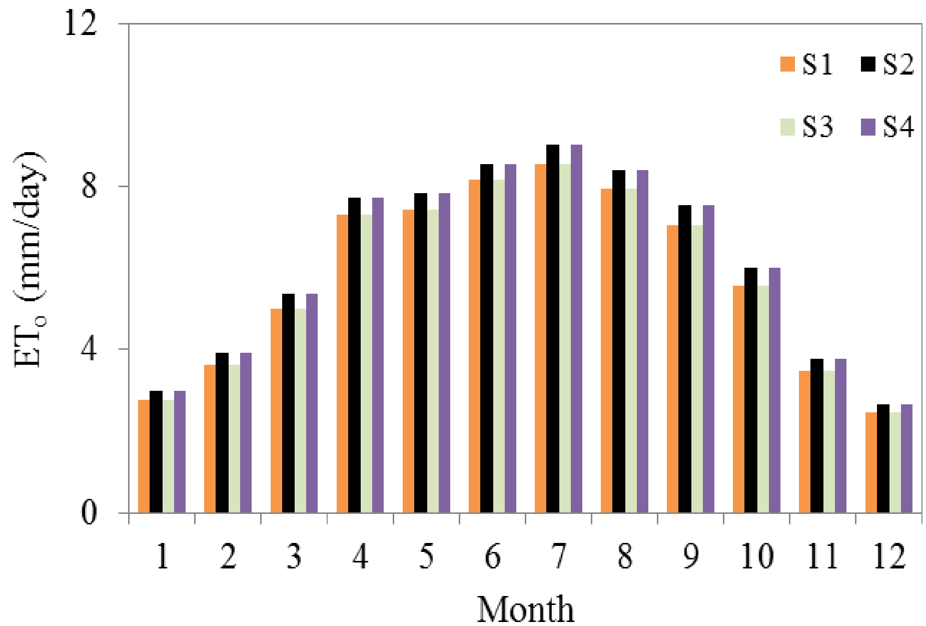

Figure 4.19: Change in ET_o from 2011 to 2050 for Tabouk region

[1-12: Jan.-Dec.]

4.8.2 Effective Rainfall (P_{eff})

In the S1 and S2 scenarios, the maximum effective rainfall was 14.6 mm/month in Nov., whereas it was zero in Jun. – Sep. and between 3 – 11.8 mm/month in the other months. The total annual effective rainfall was estimated to be 57.1 mm. The annual effective rainfall in 2050 has been predicted to be 85.9 mm/yr. In the S3 and S4 scenarios, the maximum predicted effective rainfall is about 25.6 mm/month in Jan. In Jun. – Jul. and Apr., the effective rainfall is predicted to be zero, while it is expected to be in the range of 0.4 – 16.9 mm/month in the other months (Table 4.7).

Table 4. 7: Effective rainfall in Tabouk region for S1 - S4 scenarios

Scenario	Effective Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
S1 and S2	11.8	3.0	6.9	3.0	4.0	0.0	0.0	0.0	0.0	6.9	14.6	6.9	57.1
S3 and S4	25.6	14.4	9.1	0.0	0.7	0.0	0.0	0.4	0.4	6.8	16.9	11.7	85.9

4.8.3 Crop Water Requirement (CWR)

Approximately 391, 413, 384 and 407 MCM/yr of total CWR were predicted for S1, S2, S3 and S4 scenarios respectively. The S2 and S4 scenarios will require approximately 16-22 MCM/yr of additional water than the S1 scenario.

The CWR for winter wheat was predicted to be 117, 124, 114 and 121 MCM/yr for S1, S2, S3 and S4 scenarios respectively (Tables A.7). Increase in CWR for wheat from 2011 to 2050 is approximately 4-7 MCM/yr. The CWR for vegetables was approximately 32-34 MCM/yr for S1 - S4 scenarios respectively, indicating 2 MCM/yr of increase from 2011 to 2050. The CWR for fodder crop was predicted to be 150, 159, 148 and 157 MCM/yr for the S1 - S4 scenarios respectively. Increase in CWR for the fodder crop was approximately 9 MCM/yr from 2011 to 2050. CWR for dates was approximately 46, 49, 45 and 48 MCM/yr for S1 - S4 scenarios (Figure 4.20). The increase in CWR for dates is 3 MCM/yr from 2011 to 2050. The results indicate that clover, wheat, dates and vegetables consumed approximately 38.5, 30, 11.8 and 8.3% of CWR respectively (Figure 4.21).

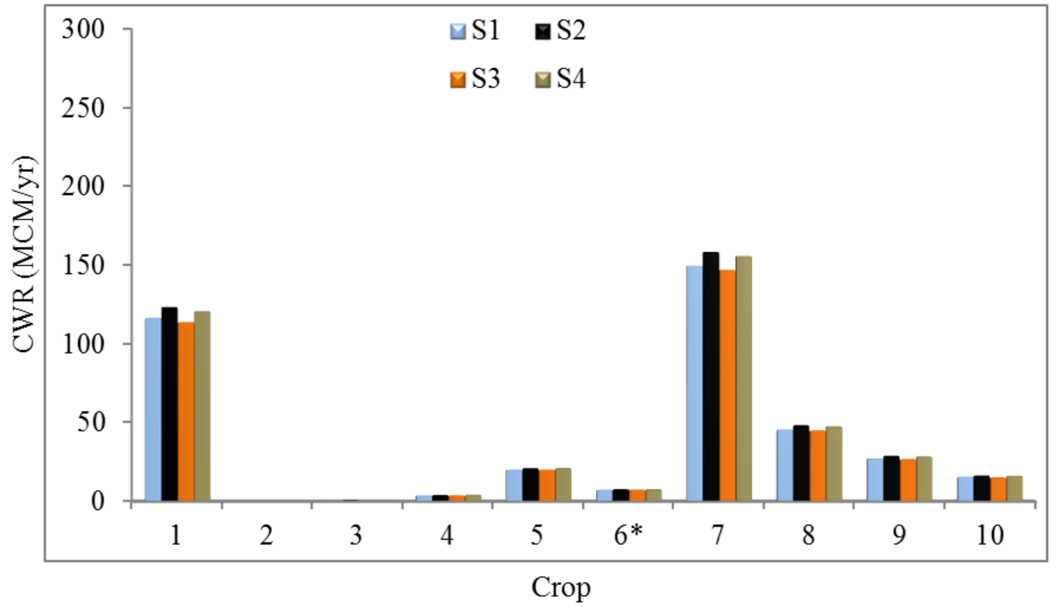

Figure 4.20: CWR for crops in Tabouk region.

[1: wheat, 2: maize, 3: barley, 4: tomato, 5: Potato, 6: other vegetables, 7: clover, 8: dates, 9: citrus and 10: grapes]; *[marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon

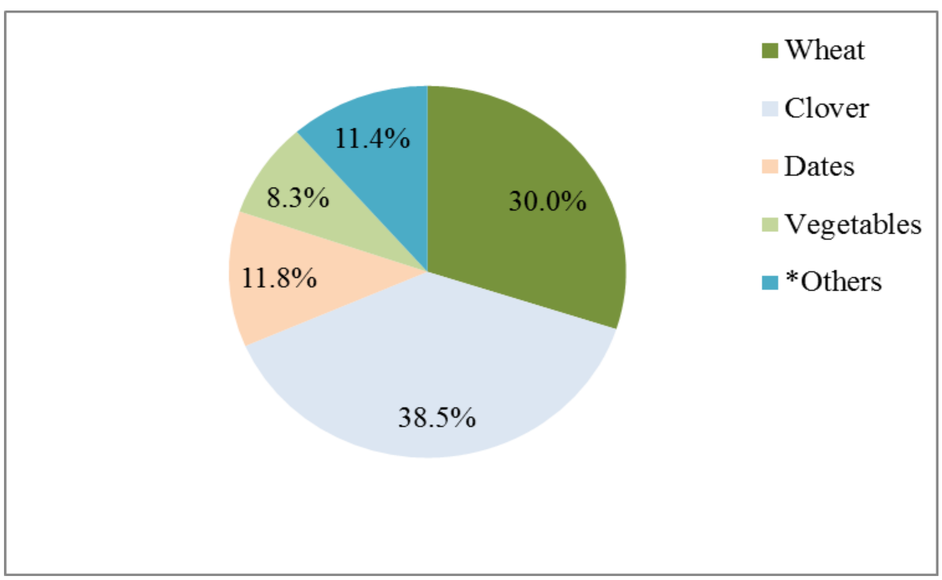

Figure 4.21: Percentage of CWR for some crops in Tabouk region

*[maize: 0.04%; barley: 0.2%; citrus: 7.1%; grapes: 4.1%]

4.9 Hail Region

4.9.1 Reference Evapotranspiration (ET_o)

The ET_o increases gradually from approximately 2.6 mm/day in Jan. to the peak value of about 9 mm/day in Jul. (Figure 4.22) Then it decreases gradually to 2.6 mm/day in Dec. (Figure 4.22). The highest ET_o were in the Jun. - Sep. period (range: 7.3 – 9 mm/day). In S2 scenario, minimum and maximum ET_o were predicted in the range of 2.8 – 9.5 mm/day. The average annual ET_o was 5.9 mm/day in 2011, which was predicted to be 6.2 mm/day in 2050 (5.8% increase). CWR may be the highest during May - Sep. and lowest during Nov. – Feb. (Figure 4.22).

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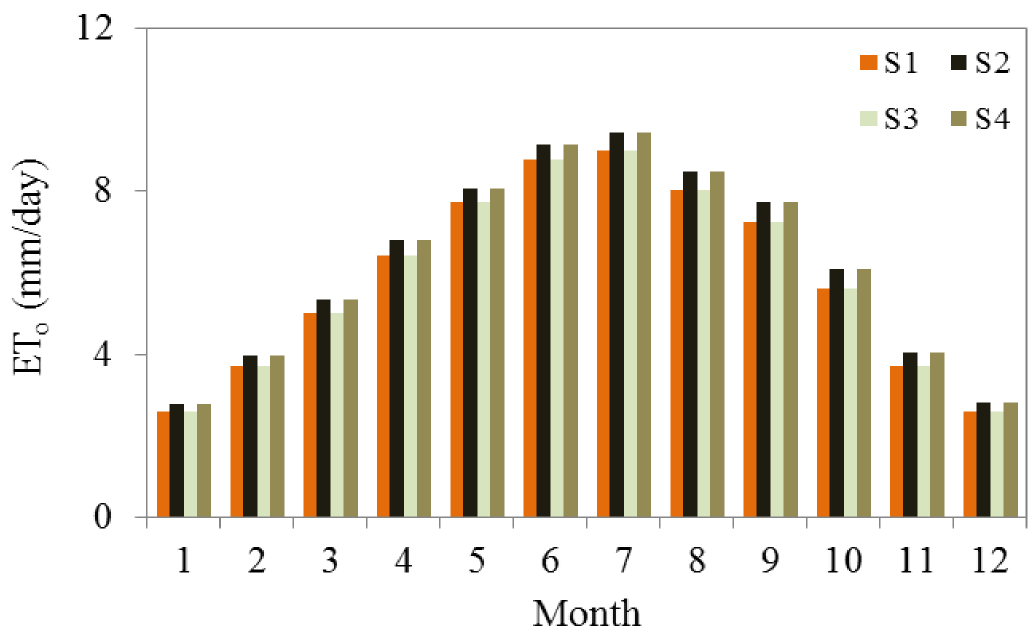


Figure 4.22: Change in ET_o from 2011 to 2050 for Hail region

[1-12: Jan.-Dec.]

4.9.2 Effective Rainfall (P_{eff})

In the S1 and S2 scenarios, the maximum effective rainfall was 45.2 mm/month in Nov., whereas it was close to zero in Jun. - Sep. and between 9.8 - 25.8 mm/month in the other months. The total annual effective rainfall was estimated to be 163.3 mm. The annual effective rainfall in 2050 has been predicted to be approximately 164.2 mm/yr. In the S3 and S4 scenarios, the maximum predicted effective rainfall is approximately 43.6 mm/month in Nov., while it is zero in Jun. – Jul. and between 2.5 – 32.1 mm/month in the other months (Table 4.8).

Table 4. 8: Effective rainfall in Hail region for S1 - S4 scenarios

Scenario	Effective Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
S1 and S2	25.8	11.8	19.4	24.9	12.7	0.0	0.0	0.0	0.0	9.8	45.2	13.7	163.3
S3 and S4	32.1	3.2	12.9	23.1	13.1	0.0	0.0	2.5	7.2	11.4	43.6	15.0	164.2

4.9.3 Crop Water Requirement (CWR)

The total CWR was predicted to be approximately 867, 919, 871 and 923 MCM/yr for S1, S2, S3 and S4 scenarios respectively. The S2 and S4 scenarios will require approximately 52-56 MCM/yr of additional water than the S1 scenario. The increase in CWR in S2 and S4 scenarios were due to the increase in temperature and small increase in effective rainfall, while the increase in S3 scenario was due to decrease in the effective rainfall during the growing periods.

The total CWR for dates was the highest followed by wheat, maize and clover. The CWR for winter wheat was predicted to be 126, 134, 129 and 137 MCM/yr for S1, S2, S3 and S4 scenarios respectively (Tables A.8). Increase in CWR for wheat is approximately 7 - 8 MCM/yr and 3 MCM/yr in the S3 scenario. The CWR for vegetables was approximately 84-88 MCM/yr for S1 - S4 scenarios respectively. Increase in CWR for vegetables is approximately 4 MCM/yr from 2011 to 2050. The CWR for fodder crop was predicted to be 113-120 MCM/yr for the S1 - S4 scenarios respectively. Increase in CWR for the fodder crop was approximately 7 MCM/yr from 2011 to 2050. CWR for dates was approximately 367-390 MCM/yr for S1 - S4 scenarios (Figure 4.23). The increase in CWR for dates is 23 MCM/yr from 2011 to 2050. The dates, wheat, maize and clover consumed approximately 42.3, 14.5, 16.6 and 13% of CWR respectively (Figure 4.24).

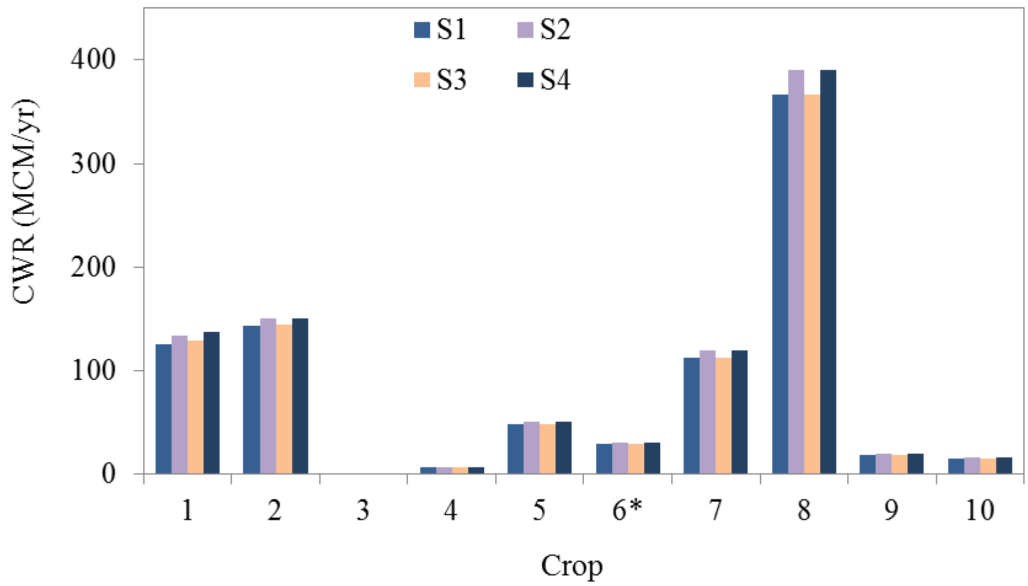


Figure 4.23: CWR for crops in Hail region.

[1: wheat, 2: maize, 3: barley, 4: tomato, 5: Potato, 6: other vegetables, 7: clover, 8: dates, 9: citrus and 10: grapes]; *[marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon]

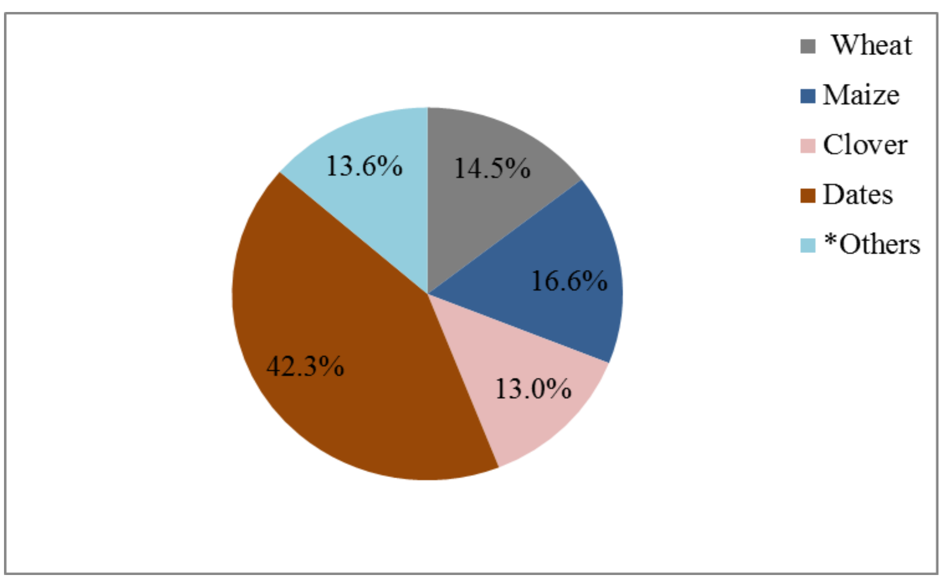


Figure 4.24: Percentage of CWR for some crops in Hail region

*[barley: 0.1%; vegetables: 9.6%, citrus: 2.2%; grapes: 1.7%]

4.10 Jazan Region

4.10.1 Reference Evapotranspiration (ET_o)

Figure 4.25 shows that the maximum ET_o at S1 scenario is approximately 7.3 mm/day. The ET_o increases steadily from approximately 4.3 mm/day in Jan. to the peak value of about 7.3 mm/day in Jul. Then it decreases gradually to 4.4 mm/day in Dec. (Figure 4.25). In S2 ET_o was minimal in Jan. (4.6 mm/day) and maximum in Jul. (7.9 mm/day). ET_o increases from 7.3 to 7.9 mm/day in Jul. for the S1 and S2 scenarios from 2011 to 2050. The average annual ET_o was 6.1 mm/day in 2011, which was predicted to be 6.5 mm/day in 2050 (6.9% increase).

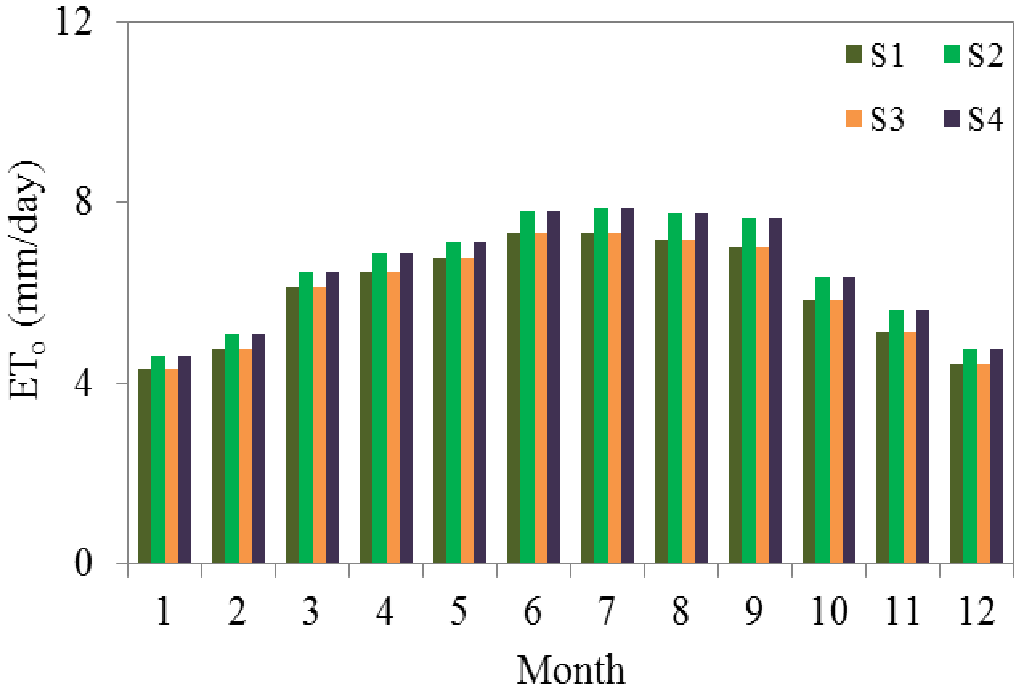


Figure 4.25: Change in ET_o from 2011 to 2050 for Jazan region

[1-12: Jan.-Dec.]

4.10.2 Effective Rainfall (P_{eff})

Table 4.9 shows that the maximum effective rainfall was 19.4 mm/month in Aug. for the S1 and S2 scenarios, whereas it was smaller in the other months (3 – 17.5 mm/month). The total annual effective rainfall was estimated to be 101.9 mm. The annual effective rainfall in 2050 has been predicted to be approximately 259.9 mm/yr. In the S3 and S4 scenarios, the predicted effective rainfall ranges between 2.5 and 68.2 mm/month in Mar.–Dec. while the minimum reaches almost zero in the months of Jan., Feb. and Jul.

Table 4. 9: Effective rainfall in Jazan region for S1 - S4 scenarios

Scenario	Effective Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
S1 and S2	4.0	3.0	10.8	17.5	3.0	4.0	5.9	19.4	5.9	4.0	8.9	15.6	101.9
S3 and S4	0.0	0.0	4.9	16.1	2.5	3.0	0.0	40.5	68.2	67.6	35.0	22.1	259.9

4.10.3 Crop Water Requirement (CWR)

This study predicted approximately 574, 615, 571 and 612 MCM/yr of total CWR for S1, S2, S3 and S4 scenarios respectively (Tables A.9). The S2 and S4 scenarios will require approximately 38-41 MCM/yr of additional water than the S1 scenario. Increase in CWR in S2 and S4 scenarios were due to the increase in temperature mainly. The main cultivated crop in this region is sorghum (92% of cultivated land) followed by millet, maize, barley, tomato, other vegetables, dates and citrus. The CWR for sorghum was predicted to be approximately 525, 563, 524 and 561 MCM/yr for S1 – S4 scenarios respectively (Tables A.9; Figure 4.26). Increase in CWR for sorghum from 2011 to 2050 has been predicted to be 36-38 MCM/yr. The CWR for tomato and other vegetables was approximately 27-28 MCM/yr for S1 - S4 scenarios respectively (Tables A.9). Increase in CWR for tomato and other vegetables is approximately 1 MCM/yr from 2011 to 2050. Increase in CWR for dates from 2011 to 2050 is approximately 0.4 MCM/yr. The results indicate that sorghum, vegetables and millet consumed approximately 91.1, 5 and 1.7% of CWR respectively (Figure 4.27).

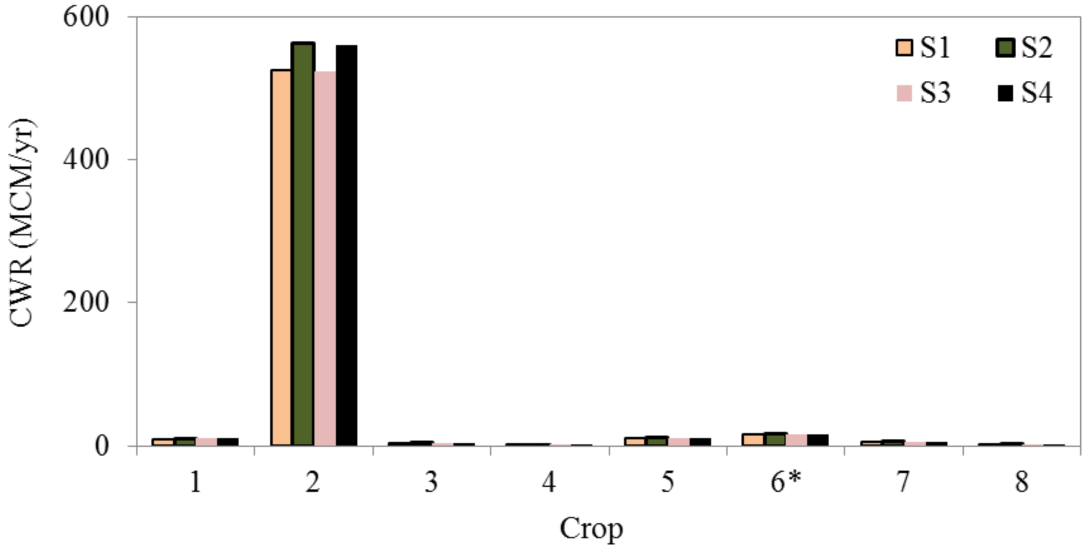


Figure 4.26: CWR for crops in Jazan region.

[1: millet, 2: sorghum, 3: maize, 4: barley, 5: tomato, 6: other vegetables, 7: dates and 8: citrus];
*[marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon]

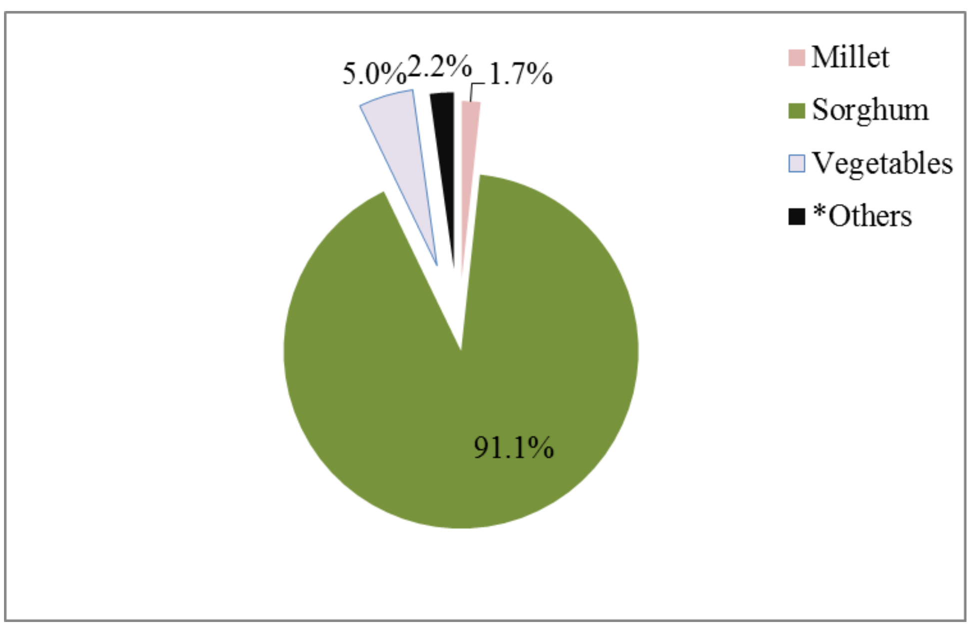


Figure 4.27: Percentage of CWR for some crops in Jazan region;

*[maize: 0.8%; barley: 0.01%; dates: 1%; citrus: 0.4%]

4.11 Najran Region

4.11.1 Reference Evapotranspiration (ET_o)

Figure 4.28 shows that the maximum ET_o at S1 scenario is about 8.6 mm/day in Jun. The ET_o increases steadily from approximately 4.4 mm/day in Jan. to the peak value of about 8.6 mm/day in Jun. Then it decreases gradually to 7.4 mm/day in Aug. After that, it increases to 8.1 mm/day in Sep. followed by the gradual decrease. The highest ET_o in the range of 5 – 8.6 mm/day in Jun - Sep. can be explained by the hot and dry summer and almost no or small rainfall in these months. In S2 scenario, similar variability was predicted. The average annual ET_o was 6.4 mm/day in 2011, which was predicted to be 6.7 mm/day in 2050 (5.1% increase).

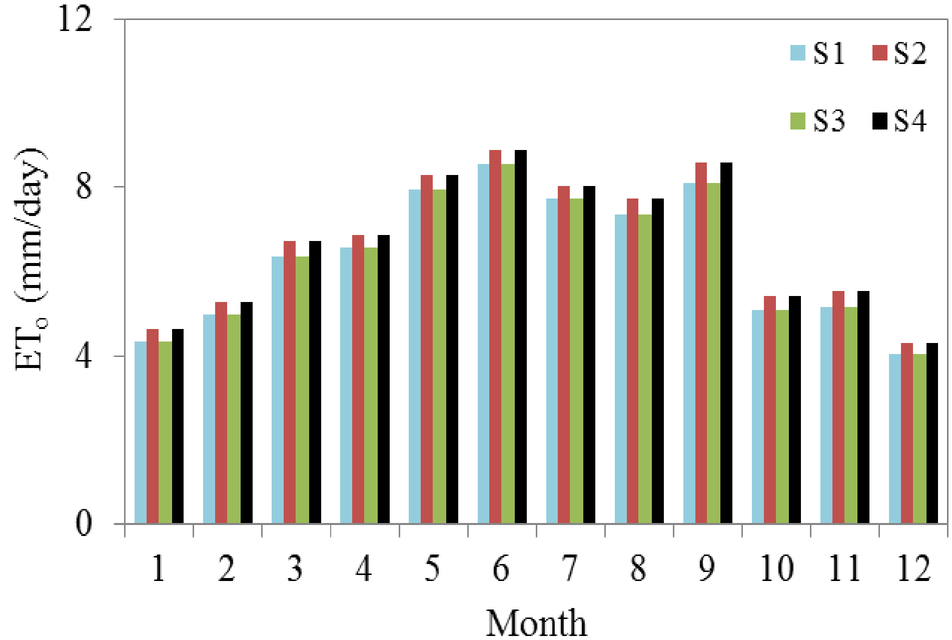


Figure 4.28: Change in ET$_o$ from 2011 to 2050 for Najran region

[1-12: Jan.-Dec.]

4.11.2 Effective Rainfall (P_{eff})

The effective rainfall showed considerable monthly variation (Table 4.10). In the S1 and S2 scenarios, the maximum effective rainfall was 62.9 mm/month in Mar., whereas it was zero in (Jun. – Jul. and Oct. – Nov.) and between 1 - 33 mm/month in the other months. The total annual effective rainfall was estimated to be 125.6 mm/yr. The annual effective rainfall in 2050 has been predicted to be approximately 169.8 mm/yr. In the S3 and S4 scenarios, the maximum predicted effective rainfall is approximately 57.7 mm/month in Mar.

Table 4. 10: Effective rainfall in Najran region for S1 - S4 scenarios

Scenario	Effective Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
S1 and S2	3.0	11.8	62.9	33.0	4.0	0.0	0.0	1.0	1.0	0.0	0.0	8.9	125.6
S3 and S4	17.5	24.3	57.7	33.8	2.5	0.0	0.0	5.8	9.7	5.9	0.0	12.5	169.8

4.11.3 Crop Water Requirement (CWR)

The total CWR was predicted to be approximately 150, 158, 147 and 155 MCM/yr of total CWR for S1, S2, S3 and S4 scenarios respectively. The S2 and S4 scenarios will require approximately 5-8 MCM/yr of additional water than the S1 scenario.

The CWR for winter wheat was predicted to be 4.7, 5, 4.6 and 5 MCM/yr for S1, S2, S3 and S4 scenarios respectively (Tables A.10). The effects of temperature and rainfall changes from 2011 to 2050 were not found to be significant. Increase in CWR for wheat from 2011 to 2050 is 0.3 MCM/yr. The CWR for vegetables was approximately 12.6, 13.1, 12.5 and 13 MCM/yr for S1 - S4 scenarios respectively. The CWR for fodder crop was predicted to be 32.1, 33.7, 31.2 and 32.9 MCM/yr for the S1 - S4 scenarios respectively. CWR for dates was approximately 72, 76, 71 and 74 MCM/yr for S1 - S4 scenarios. The increase in CWR for dates is 4 MCM/yr from 2011 to 2050. The results indicate that dates, clover citrus and vegetables consumed approximately 47.9, 21.3, 18.8 and 8.3% of CWR respectively (Figure 4.30).

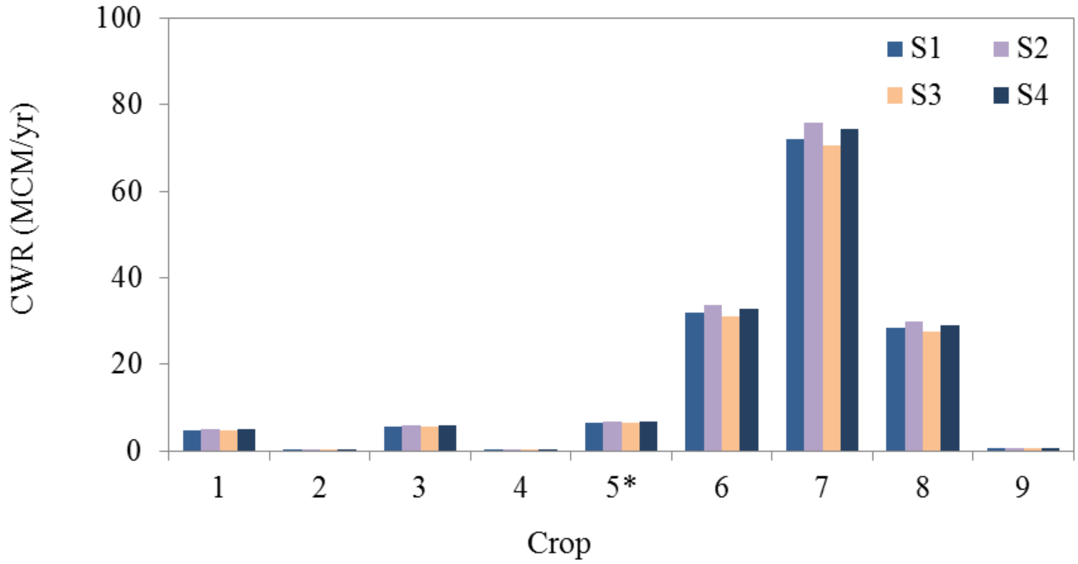


Figure 4.29: CWR for crops in Najran region.

[1: wheat, 2: barley, 3: tomato, 4: Potato, 5: other vegetables, 6: clover, 7: dates, 8: citrus and 9: grapes]; *[marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon]

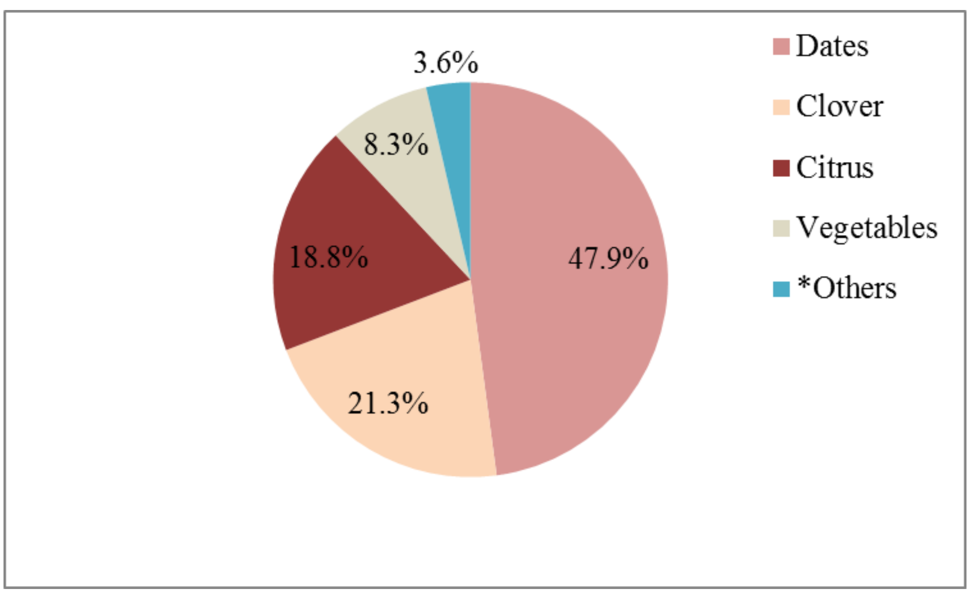


Figure 4.30: Percentage of CWR for some crops in Najran region

*[wheat: 3.2; barley: 0.1%; grapes: 0.3%]

4.12 Al-Baha Region

4.12.1 Reference Evapotranspiration (ET_o)

The ET_o for the S1 - S4 scenarios are presented in Figure 4.31. ET_o increases gradually from approximately 3.8 mm/day in Jan. to the peak value of about 7.7 mm/day in Aug. Then it decreases gradually to 3.6 mm/day in Dec. (Figure 4.31). The highest ET_o was in the range of 6.3 – 7.7 mm/day in Jun. - Oct. In S2 scenario, minimum and maximum ET_o were predicted to be in the range of 3.8 – 8.1 mm/day. In Dec., ET_o was minimal (3.8 mm/day), while in Aug., it was maximum (8.1 mm/day). The ET_o increases from 7.7 to 8.1 mm/day in Aug. for the S1 and S2 scenarios from 2011 to 2050. The average annual ET_o was 6.1 mm/day in 2011, which was predicted to be 6.4 mm/day in 2050 (5.4% increase).

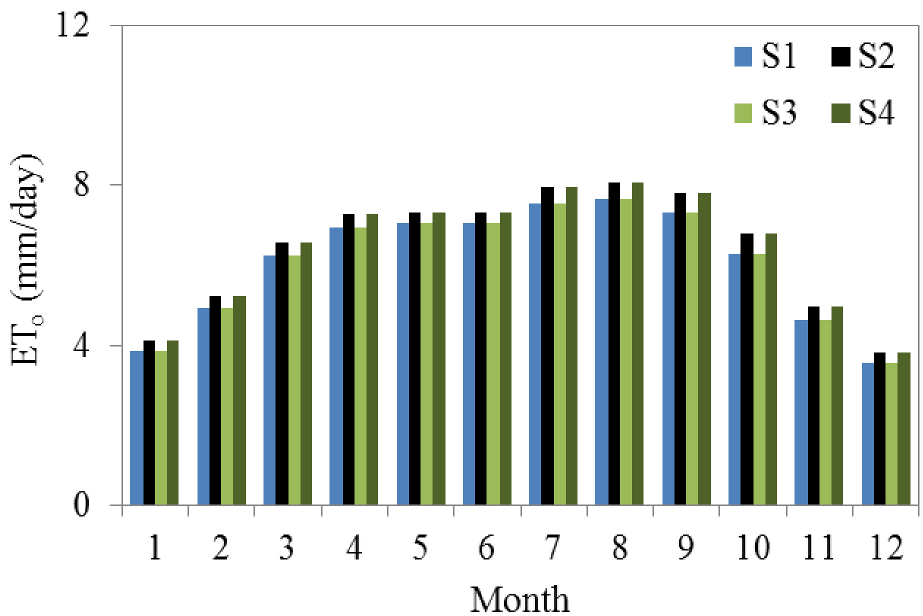


Figure 4.31: Change in ET_o from 2011 to 2050 for Al-Baha region

[1-12: Jan.-Dec.]

4.12.2 Effective Rainfall (P_{eff})

In the S1 and S2 scenarios, the maximum effective rainfall was 40.9 mm/month in Mar., whereas it was zero in Sep. and Nov. and between 1 - 40 mm/month in the other months. The total annual effective rainfall was estimated to be 117.6 mm. The annual effective rainfall in 2050 has been predicted to be approximately 226 mm/yr. In the S3 and S4 scenarios, the maximum predicted effective rainfall is about 50.2 mm/month in Oct., zero in (Jan. – Feb. and Jul.) and between 3 to 41.8 mm/month in the other months.

Table 4. 11: Effective rainfall in Al-Baha region for S1 - S4 scenarios

Scenario	Effective Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
S1 and S2	4.0	4.0	40.9	40.0	10.8	2.0	1.0	6.9	0.0	3.0	0.0	5.0	117.6
S3 and S4	0.0	0.0	35.3	40.3	10.6	3.3	0.0	25.5	41.8	50.2	5.0	14.0	226.0

4.12.3 Crop Water Requirement (CWR)

This study predicted approximately 39, 41, 37 and 39 MCM/yr of total CWR for S1, S2, S3 and S4 scenarios respectively. The S2 scenario will require approximately 2 MCM/yr of additional water than the S1 scenario. The CWR for winter wheat was predicted to be approximately 2.6, 2.8, 2.7 and 2.8 MCM/yr for S1, S2, S3 and S4 scenarios respectively (Tables A.11). The findings indicate that the effects of temperature and rainfall changes from 2011 to 2050 are not significant. Increase in CWR for wheat from 2011 to 2050 is approximately 0.1 - 0.2 MCM/yr. In case of vegetables, CWR was approximately 2.6, 2.8, 2.6 and 2.7 MCM/yr for S1 - S4 scenarios respectively. The

CWR for fodder crop was predicted to be 0.8 – 0.9 MCM/yr for the S1 - S4 scenarios respectively. CWR for dates was approximately 28.2, 29.8, 26.7 and 28.3 MCM/yr for S1 - S4 scenarios (Figure 4.32). The results indicate that dates, wheat, vegetables and grapes consumed approximately 72.7, 6.7, 6.8 and 6.3% of CWR respectively (Figure 4.33).

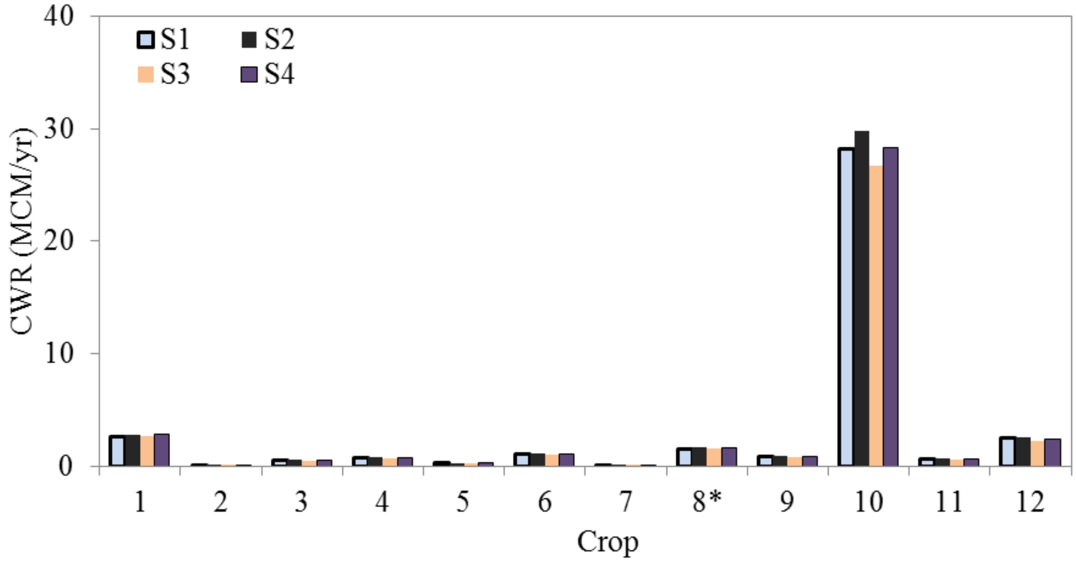


Figure 4.32: CWR for crops in Al-Baha region.

[1: wheat, 2: millet, 3: sorghum, 4: maize, 5: barley, 6: tomato, 7: Potato, 8: other vegetables, 9: clover, 10: dates, 11: citrus and 12: grapes]; *[marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon]

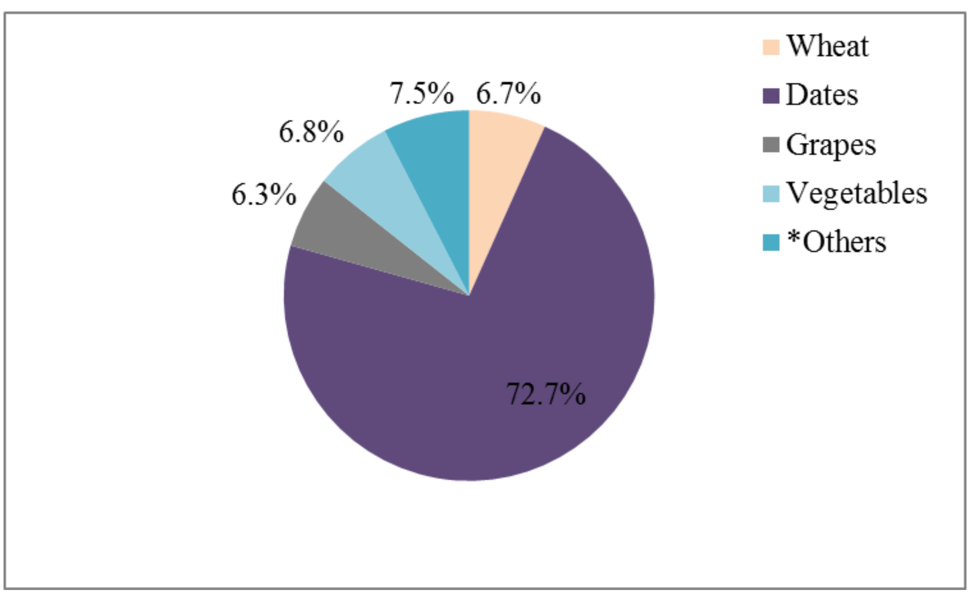


Figure 4.33: Percentage of CWR for some crops in Al-Baha region

*[millet: 0.03%; sorghum: 1.3%, maize: 1.8%; barley: 0.7%; clover: 2.1%, citrus: 1.6%]

4.13 Al-Jouf Region

4.13.1 Reference Evapotranspiration (ET_o)

The ET_o increases gradually from approximately 3 mm/day in Jan. to the peak value of about 10.9 mm/day in Jul. Then it decreases gradually to 2.6 mm/day in Dec. The highest ET_o in Jul. can be explained by the hot and dry summer, low soil moisture and almost no rainfall in this month. In S2 scenario, minimum and maximum ET_o were predicted to be in the range of 2.8 - 11.5 mm/day. Comparison between S1 and S2 shows that ET_o increases from 10.9 to 11.5 mm/day in Jul. from 2011 to 2050. The yearly average of ET_o was 6.9 mm/day in 2011, which was predicted to be 7.3 mm/day in 2050 (6% increase). The S3 and S4 scenarios are almost similar to the S1 and S2 scenarios respectively (Figure 4.34).

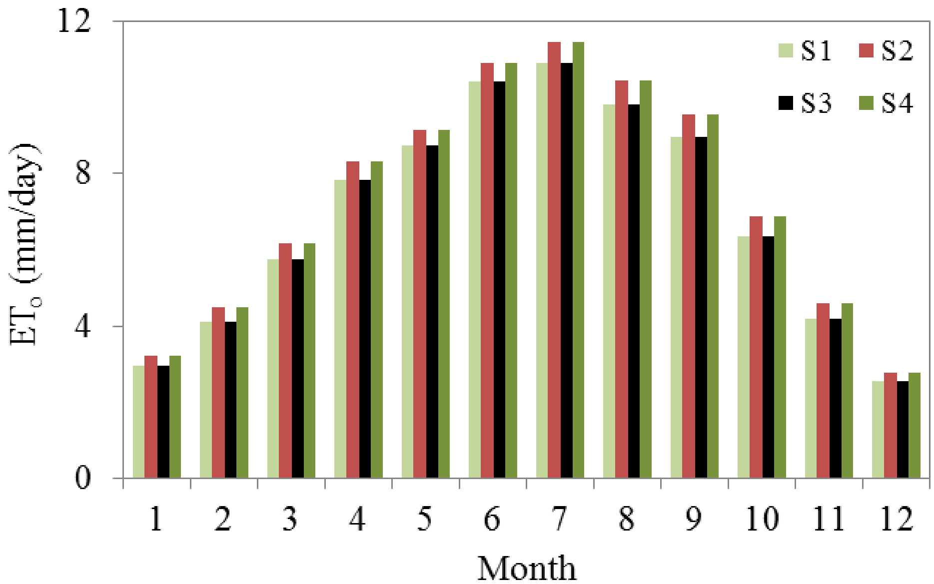


Figure 4.34: Change in ET_o from 2011 to 2050 for Al-Jouf region

[1-12: Jan.-Dec.]

4.13.2 Effective Rainfall (P_{eff})

The effective rainfall showed considerable monthly variation (Table 4.12). The maximum effective rainfall was 13.7 mm/month in Apr, whereas it was close to zero in May, Jul. - Sep. and between 2 - 9.8 mm/month in the other months. The total annual effective rainfall was estimated to be 57.1 mm. The annual effective rainfall in 2050 has been predicted to be approximately 65.8 mm/yr.

Table 4. 12: Effective rainfall in Al-Jouf region for S1 - S4 scenarios

Scenario	Effective Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
S1 and S2	8.9	3.0	7.9	13.7	0.0	2.0	0.0	0.0	0.0	9.8	4.0	7.9	57.1
S3 and S4	16.5	0.0	5.9	10.2	0.0	2.0	0.0	2.4	7.1	11.3	2.2	8.1	65.8

4.13.3 Crop Water Requirement (CWR)

This study predicted approximately 873, 930, 874 and 931 MCM/yr of total CWR for S1, S2, S3 and S4 scenarios respectively. The S2 and S4 scenarios will require approximately 57-58 MCM/yr of additional water than the S1 scenario. The increase in CWR in S2 and S4 scenarios were due to the increase in temperature mainly. The effects of rainfall changes (S3 scenario) were predicted to be minimal (e.g., 1 MCM/yr.) due to small decrease in the effective rainfall during the growing periods. The CWR for winter wheat was predicted to be 476, 507, 480 and 510 MCM/yr for S1, S2, S3 and S4 scenarios respectively (Tables A.12). The findings reflected no significant effects from rainfall changes from 2011 to 2050 (e.g,, 4 MCM/yr of increase in CWR), while the changes in temperature showed significant effects. Increase in CWR for wheat from 2011 to 2050 is approximately 31-34 MCM/yr (Figure 4.35). The CWR for vegetables was approximately 34-36 MCM/yr for S1 - S4 scenarios respectively, indicating 2 MCM/yr increase from 2011 to 2050. The CWR for fodder crop was predicted to be 188, 201, 187 and 200 MCM/yr for the S1 - S4 scenarios respectively. CWR for dates was approximately 129, 137, 128 and 137 MCM/yr for S1 - S4 scenarios. The results indicate that wheat, clover and dates consumed about 54.6, 21.5 and 14.8% of CWR respectively (Figure 4.36).

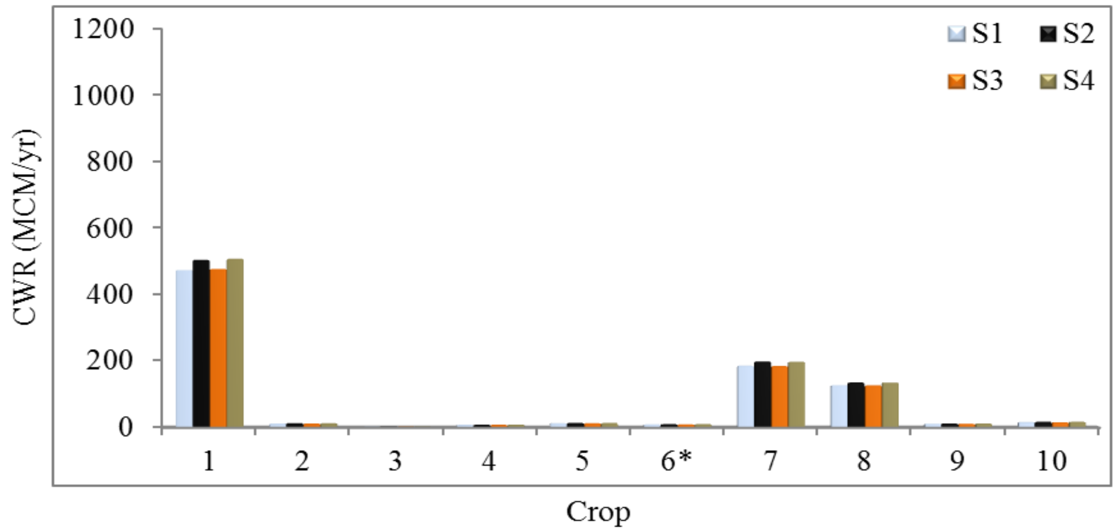


Figure 4.35: CWR for crops in Al-Jouf region.

[1: wheat, 2: maize, 3: barley, 4: tomato, 5: Potato, 6: other vegetables, 7: clover, 8: dates, 9: citrus and 10: grapes]; *[marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon]

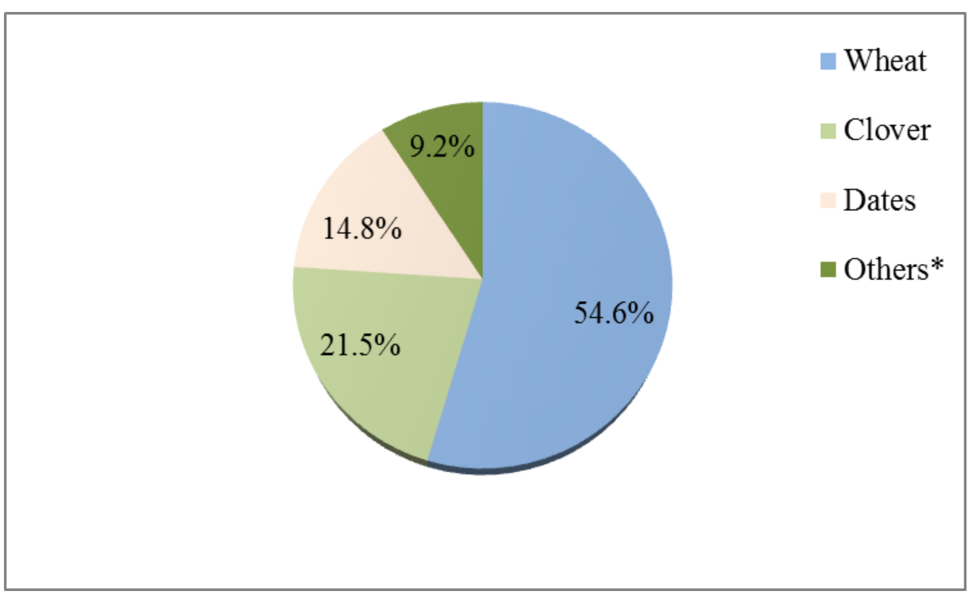


Figure 4.36: Percentage of CWR for some crops in Al-Jouf region

*[maize: 1.5%; barley: 0.3%; vegetables: 3.9%; citrus: 1.5%; grapes: 2%]

4.14 Comparing Results

Significant increase in CWR was predicted in most regions for the S2 and S4 scenarios. The increase in CWR was mainly due to the increase in temperature, while the effects of rainfall were not significant in many regions. The monthly average increase in temperature was predicted to be in the range of 2.1 - 3.8°C. The highest increase in temperature was observed in the summer months (e.g., May – Sep.), indicating higher rates of ET_o during this period. A number of crops are grown during the summer months, which might consume proportionately more water than the other seasons. In addition, some crops can have their mid-season of growing stage during the summer months, which can have high values of K_c, leading to higher CWR. For example, K_c values in the mid-season ranges between 1 and 1.20 for wheat, millet, maize, sorghum, barley, Tomato, potato and other vegetables (Table 3.8). This study predicted the CWR for the total cultivated area (722 thousand hectares) in the Kingdom in 2009 [7]. The total CWR for all crops were predicted to be 8713, 9221, 8667 and 9176 MCM/yr for the S1, S2, S3 and S4 scenarios respectively. The increase in CWR from 2011 to 2050 in the S2 scenario is approximately 508 MCM/yr. The increase in CWR in the S4 scenario was estimated to be 463 MCM/yr. In the S3 scenario, the CWR may be decreased by approximately 47 MCM/yr from 2011 to 2050 possibly, due to increase in rainfall in 2050. Referring to each region, Riyadh has the highest CWR followed by Qaseem, Al-Jouf and Hail (Table 4.25, Figure 4.37). The total CWR for all crops in Riyadh were predicted to be 2802, 2951, 2797 and 2945 MCM/yr for the S1, S2, S3 and S4 scenarios respectively. The increase in CWR for Riyadh is about 148 and 143 MCM/yr for the S2 and S4 scenario from 2011 – 2050. For the S3 scenario, the CWR is predicted to decrease by 6 MCM/yr from 2011 - 2050. Qaseem is the second region in terms of CWR. The total CWR was predicted to be 1426, 1505, 1413 and 1494 MCM/yr for the S1, S2, S3 and S4 scenarios respectively (Figure 4.37). The increase in CWR is about 79 and 68 MCM/yr for the S2 and S4 scenario from 2011 – 2050. For the S3 scenario, the CWR is predicted to decrease by 13 MCM/yr from 2011 - 2050. Al-Jouf is the third largest area in terms of CWR. The total CWR for all crops in Al-Jouf were predicted to be 873, 930, 874 and 931 MCM/yr for the S1, S2, S3 and S4 scenarios respectively. The increase in CWR is about 57 and 59 MCM/yr for the S2 and S4 scenario from 2011 – 2050. For the S3 scenario, the CWR is predicted to increase by 1 MCM/yr from 2011 – 2050 due to the decrease in the effective rainfall especially during wheat growing period (Jan. - May). Further details in CWR for the other regions are presented in Table 4.25.

Table 4. 13: Expected total CWR in Saudi Arabia from 2011 - 2050**.**

Regions	Total CWR in Each Scenario (MCM/yr)			
	S1	S2	S3	S4
Riyadh	2802	2951	2797	2945
Makkah	402	431	398	426
Madinah	558	586	554	582
Qaseem	1426	1505	1413	1494
Eastern Region	485	517	480	512
Aseer	146	155	141	151
Tabouk	391	413	384	407
Hail	867	919	871	923
Jazan	574	615	571	612
Najran	150	158	147	155
Al-Baha	39	41	37	39
Al-Jouf	873	930	874	931
Total	8713	9221	8667	9176

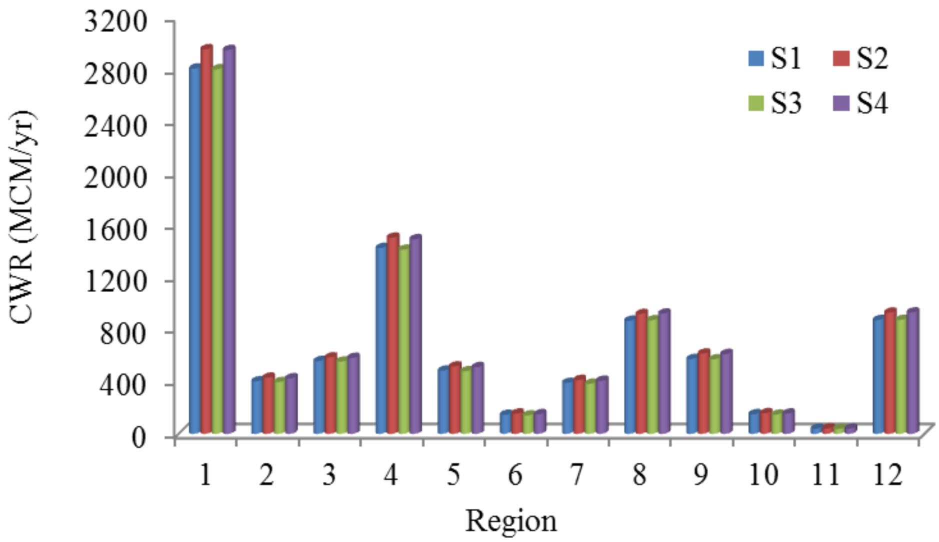


Figure 4.37: Predicted total CWR for each region in Saudi Arabia under different scenarios

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

Overall, the CWR for dates is the highest, followed by clover and wheat, representing approximately 40, 21 and 14% of total CWR (Figure 4.38). The CWR for vegetables and sorghum are approximately 10 and 7% of the total CWR, while the remaining 8% is accounted for the other crops (millet, maize, barley, citrus and grapes).

In the Kingdom, the CWR for dates were predicted to be 3492, 3696, 3464 and 3668 MCM/yr for the S1, S2, S3 and S4 scenarios (Figure 4.38). Increase in CWR for dates is about 204 and 176 MCM/yr from 2011 to 2050 for the S2 and S4 scenarios respectively. The CWR for the S3 scenario is predicted to decrease by 27 MCM/yr from 2011 to 2050. This decrease is due to the increase in the rainfall, while temperature change was not included. The CWR for dates contributes approximately 30, 24, 12, 11, 7 and 6% to the total CWR in Riyadh, Qaseem, Madinah, Hail, Eastern region and Makkah respectively (Figure 4.39). Figure 4.40 shows that the CWR for dates are higher during May – Aug. for the S1 – S4 scenarios in Riyadh. In S1 scenario, monthly CWR was predicted to be in the range of 309 – 339 mm/month during Jun. – Aug., while it was 325 – 355 mm/month for the S2 scenario (Figure 4.40). In Riyadh, annual CWR for dates was predicted to increase from 1032 in the S1 scenario to 1088 MCM/yr and 1085 in the S2 and S4 scenarios. The total increase is approximately 56 and 53 MCM/yr from 2011 – 2050 respectively. The CWR was also predicted to decrease to about 1028 MCM/yr for the S3 scenario (Figure 4.39). The variability of CWR for Qaseem and Madinah are presented in Figures 4.41 - 4.42, while these figures show similar characteristics.

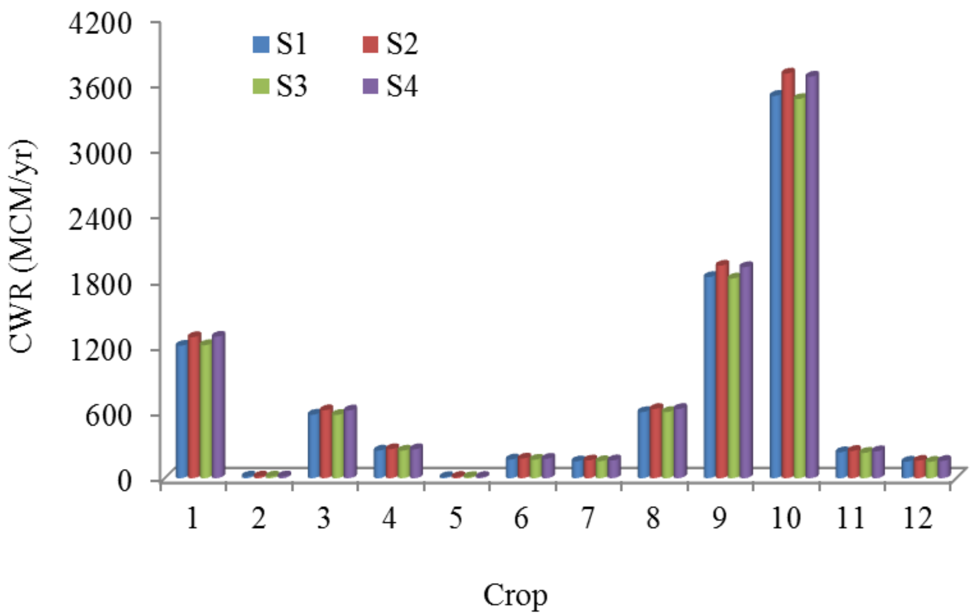


Figure 4.38: Predicted CWR for different crops in S1-S4 scenarios in Saudi Arabia.

[1: wheat, 2: millet, 3: sorghum, 4: maize, 5: barley, 6: tomato, 7: Potato, 8: other vegetables, 9: clover, 10: dates, 11: citrus and 12: grapes]

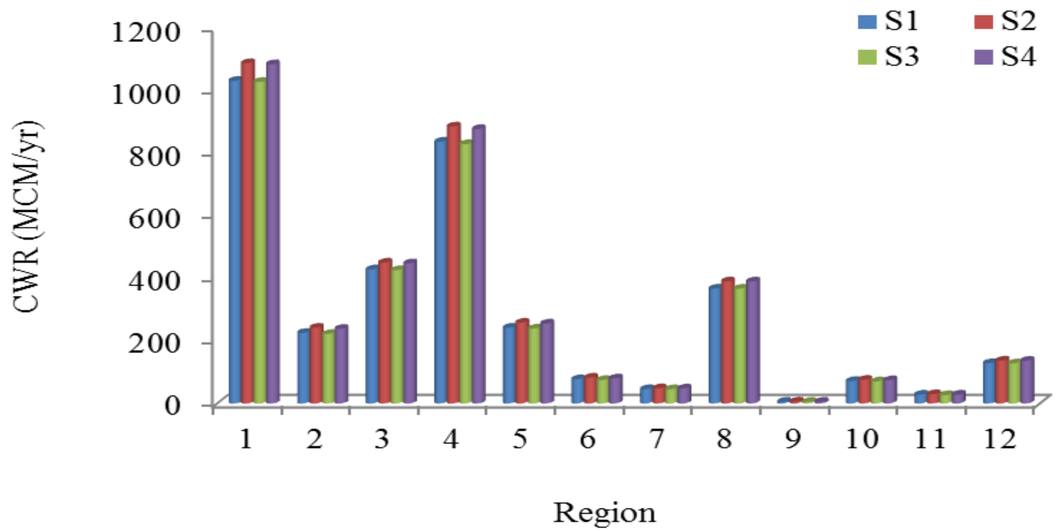


Figure 4.39: CWR in producing dates in Saudi Arabia.

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

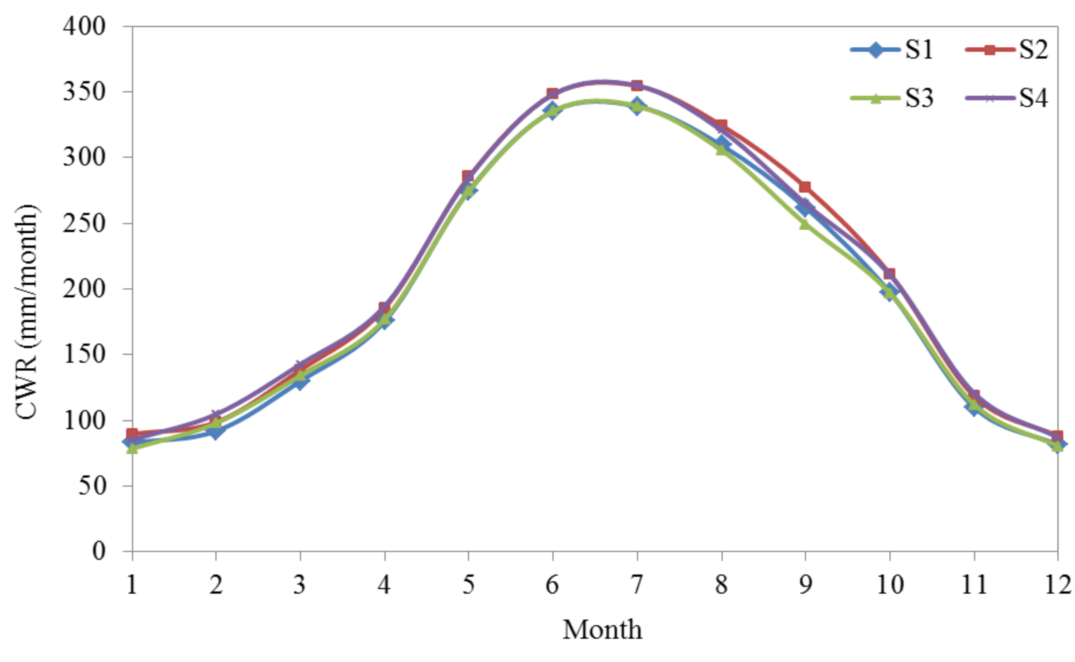


Figure 4.40: Monthly CWR for dates in Riyadh region under different scenarios.

[1-12: Jan.-Dec.]

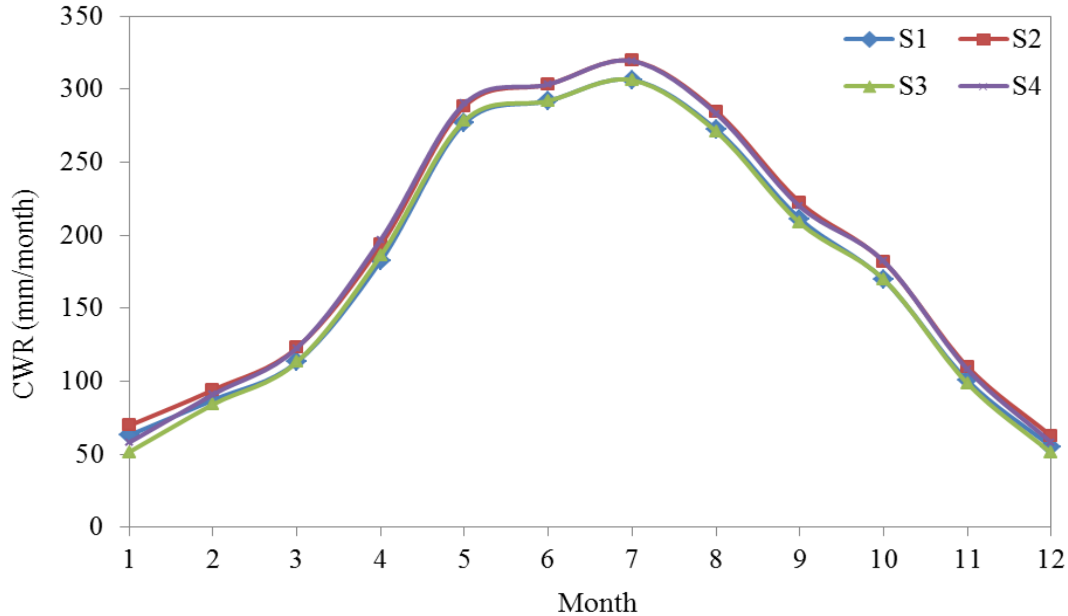


Figure 4.41: Monthly CWR for dates in Qaseem region under different scenarios.

[1-12: Jan.-Dec.]

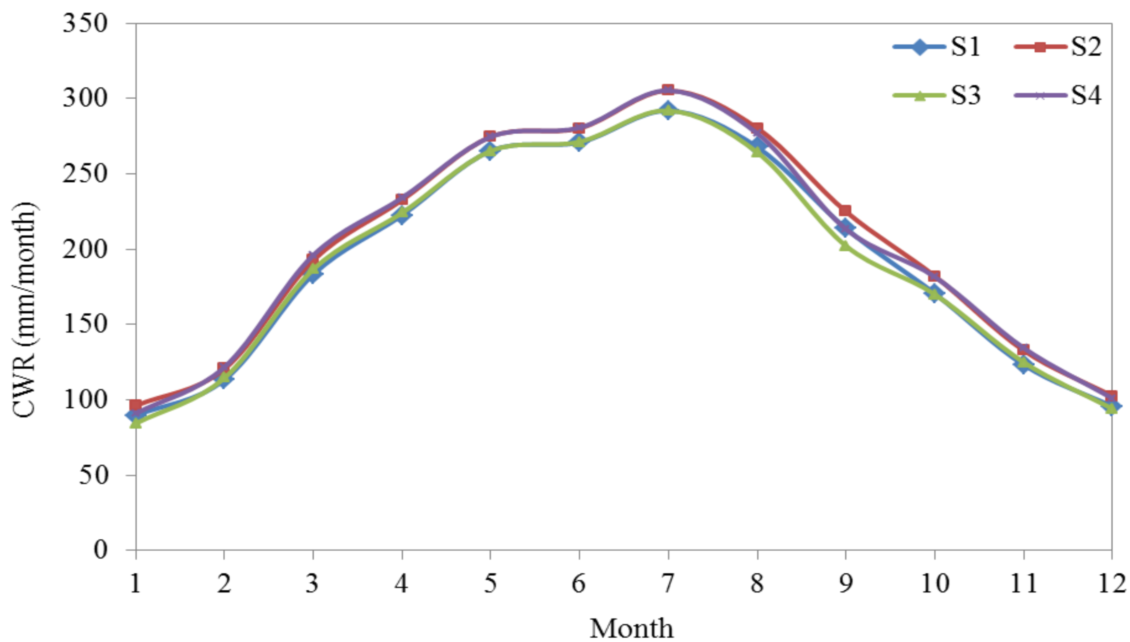


Figure 4.42: Monthly CWR for dates in Madinah region under different scenarios.

[1-12: Jan.-Dec.]

For clover, the CWR was predicted to be 1837, 1941, 1824 and 1928 for the S1, S2, S3 and S4 scenarios in all regions respectively (Figure 4.38). The increase in CWR is 104 and 91 MCM/yr from 2011 to 2050 for the S2 and S4 scenarios respectively (Figure 4.38). The CWR for the S3 scenario is predicted to decrease by 13 MCM/yr from 2011 – 2050. The regions of Riyadh, Qaseem, Al-Jouf, Tabouk and Hail consume 54, 14, 10, 8 and 6% of CWR for clover in Saudi Arabia, while the remaining 8% of CWR was consumed in Madinah, Eastern region, Najran, Aseer, Makkah and Al-Baha (Figure 4.43). In S1 scenario, monthly CWR was predicted to be 271 – 327 mm/month during May – Aug. The CWR is predicted to increase to 282 – 343 mm/month during the same period for the S2 and S4 scenarios (Figure 4.44).

The similar trend was observed for Qaseem region (Figure 4.45). The monthly CWR for clover was predicted to be 265 – 293 mm/month during May – Jul. for the S1 scenario, which is predicted to increase to 276 – 306 mm/month for the S2 scenario during the same period. In Qaseem, annual CWR was predicted to increase from 252 MCM/yr in the S1 scenario to 267 MCM/yr and 264 MCM/yr for the S2 and S4 scenarios (Figure 4.45). The CWR was predicted to decrease to 249 MCM/yr for the S3 scenario. In Al-Jouf, monthly CWR was predicted to be 109 – 263 mm/month during May – Sep. for the S1 scenario, which is predicted to increase to 114 – 279 mm/month for the S2 scenario during the same period (Figure 4.46). Annual CWR was predicted to increase from 188 MCM/yr for the S1 scenario to 200 MCM/yr in S2 scenario. Due to the differences in the growing seasons, the highest monthly CWR was observed in Jul. in Riyadh and Qaseem regions, while it was observed in Sep. in the Al-Jouf region.

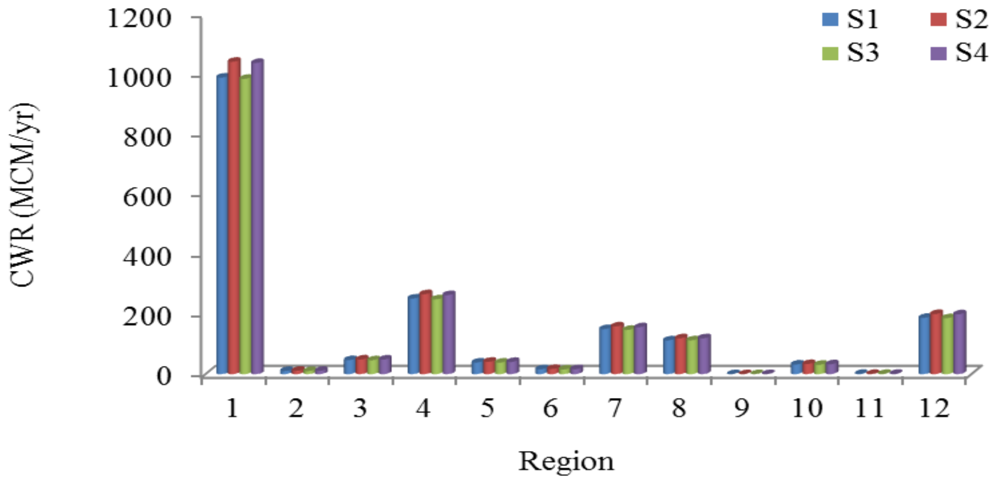


Figure 4.43: CWR in producing clover in Saudi Arabia.

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

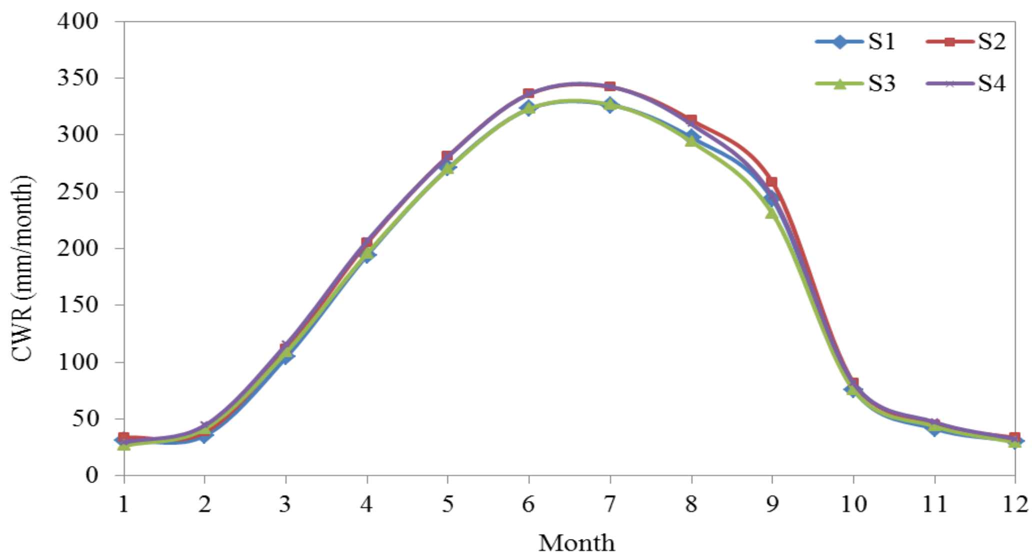


Figure 4.44: Monthly CWR for clover in Riyadh region under different scenarios.

[1-12: Jan.-Dec.]

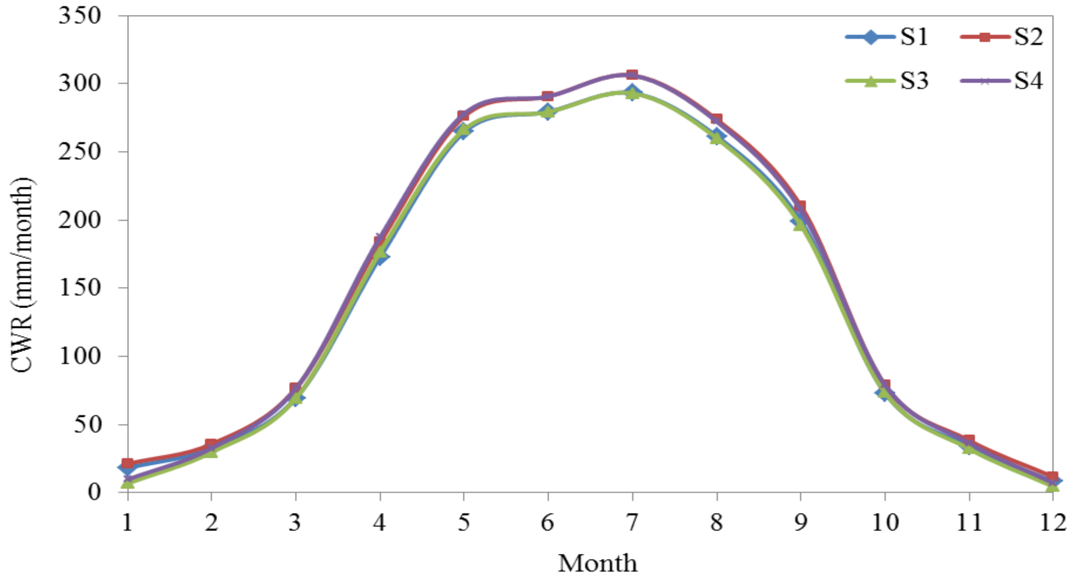


Figure 4.45: Monthly CWR for clover in Qaseem region under different scenarios.

[1-12: Jan.-Dec.]

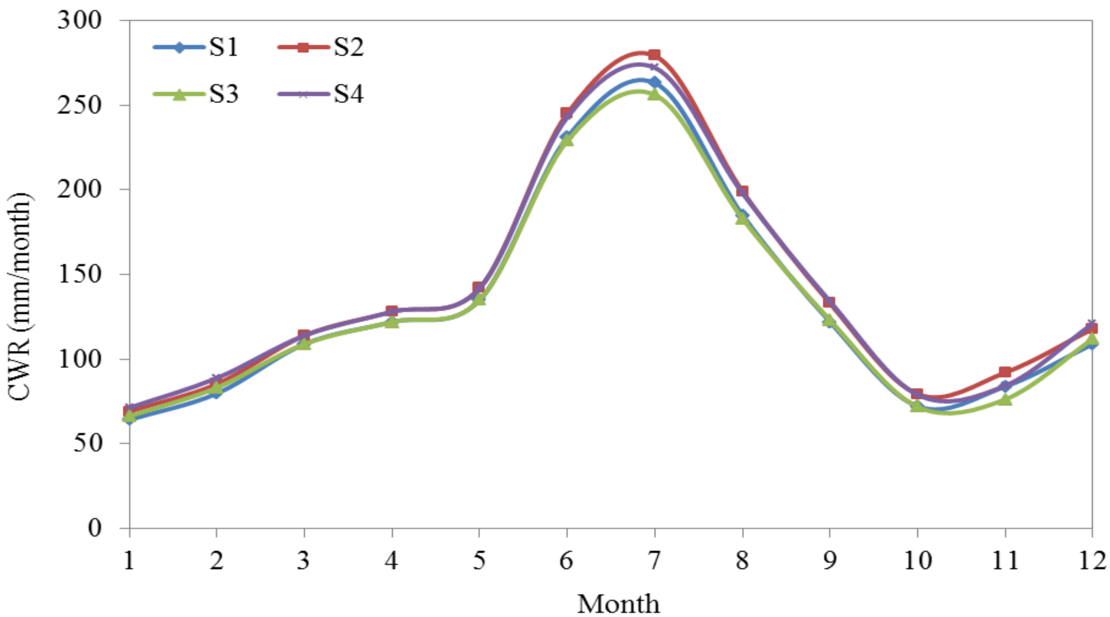


Figure 4.46: Monthly CWR for clover in Al-Jouf region under different scenarios.

[1-12: Mar. - Feb.]

In the Kingdom, the CWR for wheat was predicted to be 1210, 1288, 1215 and 1293 MCM/yr for the S1, S2, S3 and S4 scenarios (Figure 4.38). The increase in CWR is approximately 78 and 83 MCM/yr from 2011 to 2050 for the S2 and S4 scenarios respectively. The CWR for the S3 scenario is predicted to increase by 5 MCM/yr from 2011 – 2050. The increase in CWR for the S2 and S4 scenarios was due to increase in temperature mainly, while the increase in CWR in the S3 scenario was due to decrease in effective rainfall. Wheat is the largest water consuming crop in Al-Jouf region followed by Riyadh, Eastern, Qaseem, Hail and Tabouk, representing approximately 39.4, 16.5, 11.2, 10.9, 10.4 and 9.7% of total CWR in the Kingdom respectively (Figure 4.47). Figures (4.48– 4.50) show the monthly CWR for wheat in Al-Jouf, Riyadh and Eastern regions respectively. In Al-Jouf and Riyadh regions, the behavior of monthly CWR for wheat is almost the same. In the S1 scenario, the monthly CWR for wheat was predicted to be in the range of 26 – 266 and 27 – 233 mm/month in Al-Jouf and Riyadh during Jan. – May respectively. These estimated to increase to 29 – 283 and 29 – 246 mm/month for S2 scenario during the same period. In Eastern region, monthly CWR is lower than the monthly CWR in Al-Jouf and Riyadh regions Figure (4.50). However, the cultivated area for wheat in Al-Jouf is higher (65162 hectares) followed by Riyadh (30896 hectares) and Eastern region (30691 hectares).

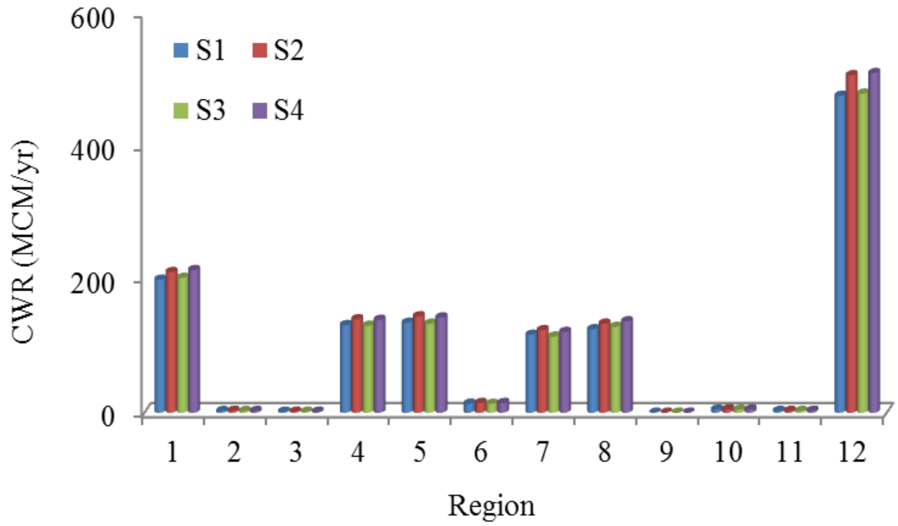


Figure 4.47: CWR in producing wheat in Saudi Arabia.

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

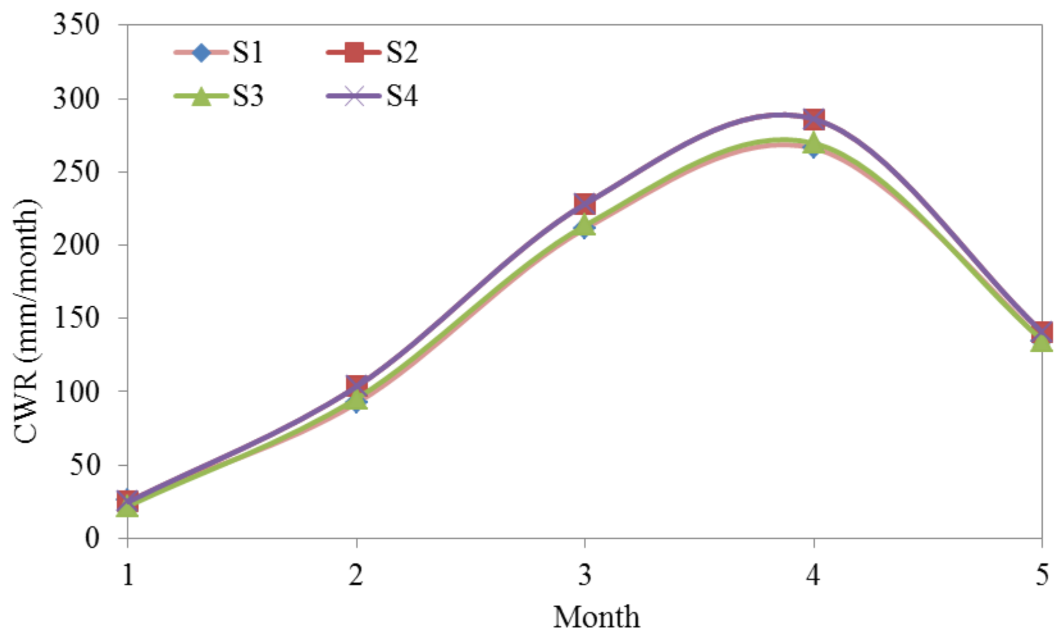


Figure 4.48: Monthly CWR for wheat in Al-Jouf region under different scenarios.

[1-5: Jan. - May]

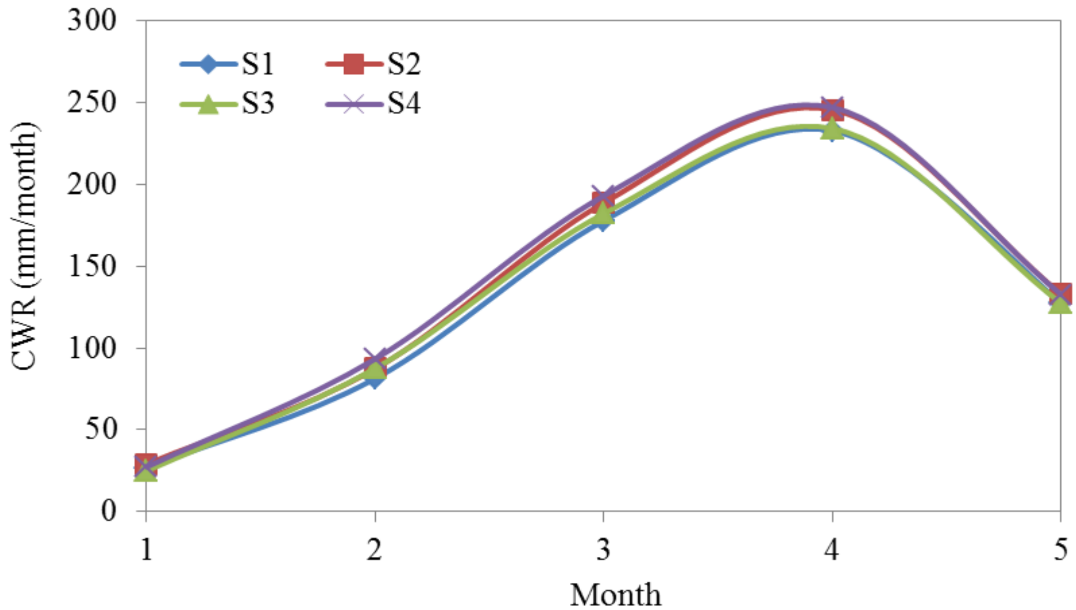


Figure 4.49: Monthly CWR for wheat in Riyadh region under different scenarios.

[1-5: Jan. - May]

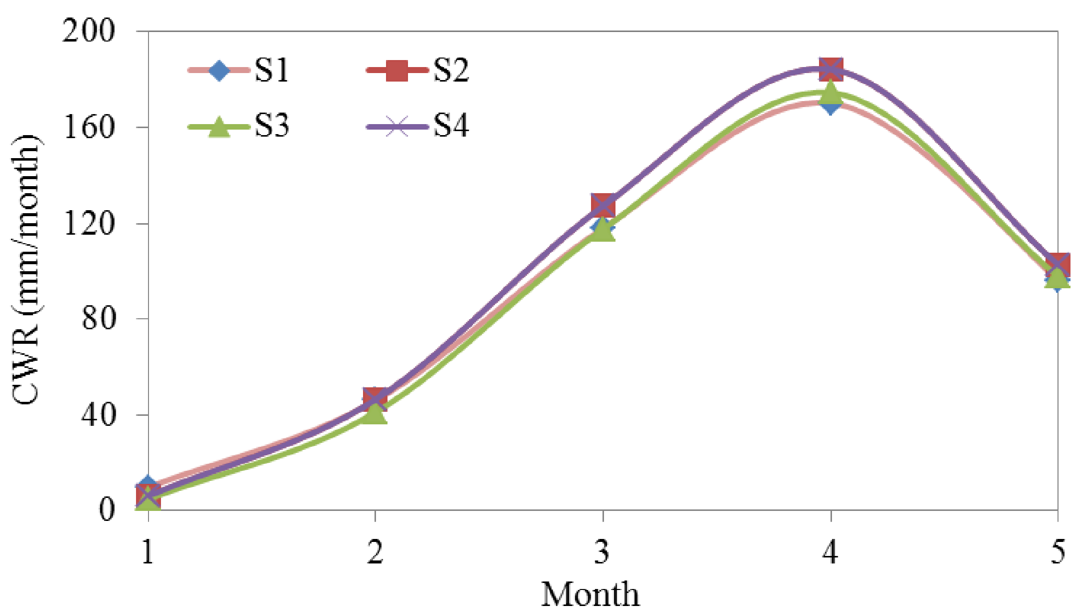


Figure 4.50: Monthly CWR for wheat in Eastern region under different scenarios.

[1-5: Jan. - May]

The CWR for a group of vegetables (marrow, eggplant, okra, carrot, dry onion, cucumber, melon and watermelon) were predicted to be 603, 632, 604 and 633 MCM/yr for the S1, S2, S3 and S4 scenarios respectively (Figure 4.38). The increase in CWR is approximately 29 MCM/yr from 2011 to 2050 for the S2 and S4 scenarios, while in the S3 scenario, CWR is predicted to decrease by 0.6 MCM/yr from 2011 – 2050. The CWR for these vegetables in Riyadh region was predicted to be highest (371 - 388 MCM/yr), followed by Makkah (59 – 63 MCM/yr), Qaseem (55 – 57 MCM/yr), Eastern region (35 - 37 MCM/yr) and Hail (28 – 30 MCM/yr) for the S1 – S4 scenarios.

The total CWR for sorghum was predicted to be 580 - 620 MCM/yr for the S1 – S4 scenarios, representing a 40 MCM/yr of CWR increase from 2011 - 2050. The CWR for sorghum in Jazan region was predicted to be highest (525 - 563 MCM/yr), followed by Makkah (36 – 38 MCM/yr), Aseer (10 – 11 MCM/yr), Riyadh (8 – 9 MCM/yr) and Al-Baha (0.50 MCM/yr) for the S1 – S4 scenarios.

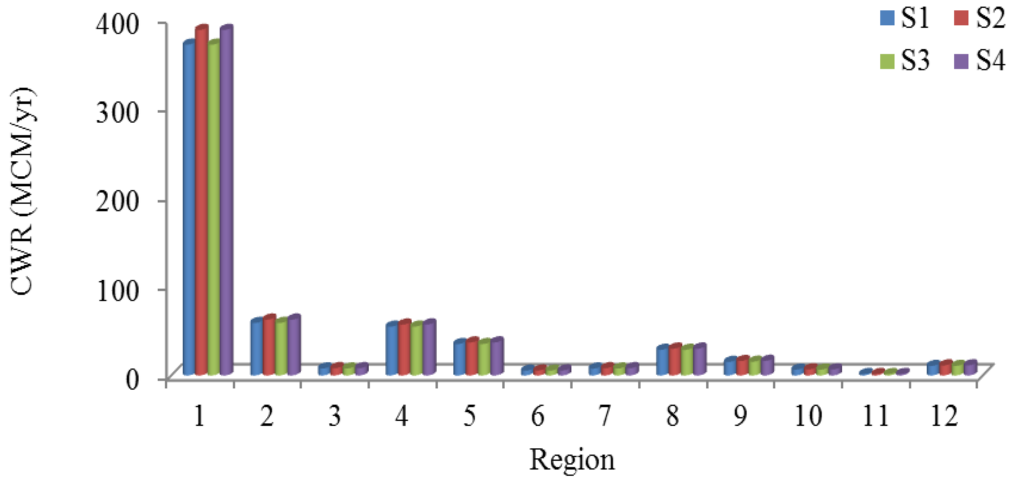


Figure 4.51: CWR in producing vegetables in Saudi Arabia.

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

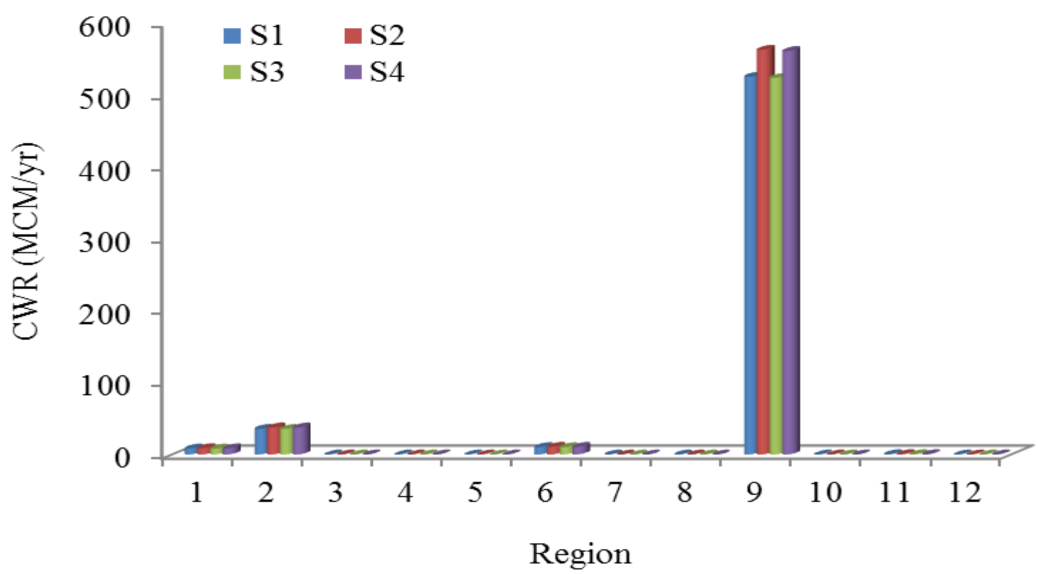


Figure 4.52: CWR in producing sorghum in Saudi Arabia.

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

The total CWR for maize was predicted to be in the range of 252 – 264 MCM/yr for the S1 – S4 scenarios (Figure 4.38). The CWR in the Hail region was predicted to be highest (143 – 151 MCM/yr), followed by Qaseem (58 – 60 MCM/yr), Riyadh (23– 25 MCM/yr), Al-Jouf (13 - 14 MCM/yr), Makkah (4.8 – 5.1 MCM/yr), Jazan (4 – 5 MCM/yr) and Eastern region (2 - 2.50 MCM/yr) for the S1 – S4 scenarios. There was no cultivated area for maize in Najran and the CWR for the other regions are not significant (Figure 4.53)

The CWR for citrus was predicted to be in the range of 237 – 249 MCM/yr for the S1 – S4 scenarios (Figure 4.38). The CWR for citrus was predicted to be the highest in Riyadh (61 – 65 MCM/yr), followed by Qaseem (30 – 32 MCM/yr), Najran (28– 30 MCM/yr), Tabouk (28 - 29 MCM/yr), Makkah (26 – 28 MCM/yr), Al-Jouf and Madinah (13 MCM/yr) and Eastern region (10 - 11 MCM/yr) for the S1 – S4 scenarios (Figure 4.54).

The total CWR for tomato was predicted to be 167 – 180 MCM/yr for the S1 – S4 scenarios. The CWR for tomato in Riyadh region was predicted to be highest (59 – 62 MCM/yr), followed by Makkah (20 – 22 MCM/yr), Eastern region (17– 18 MCM/yr), Madinah (12 - 13 MCM/yr), etc. The CWR for the other regions ranges between 1 and 11 MCM/yr (Figure 4.55).

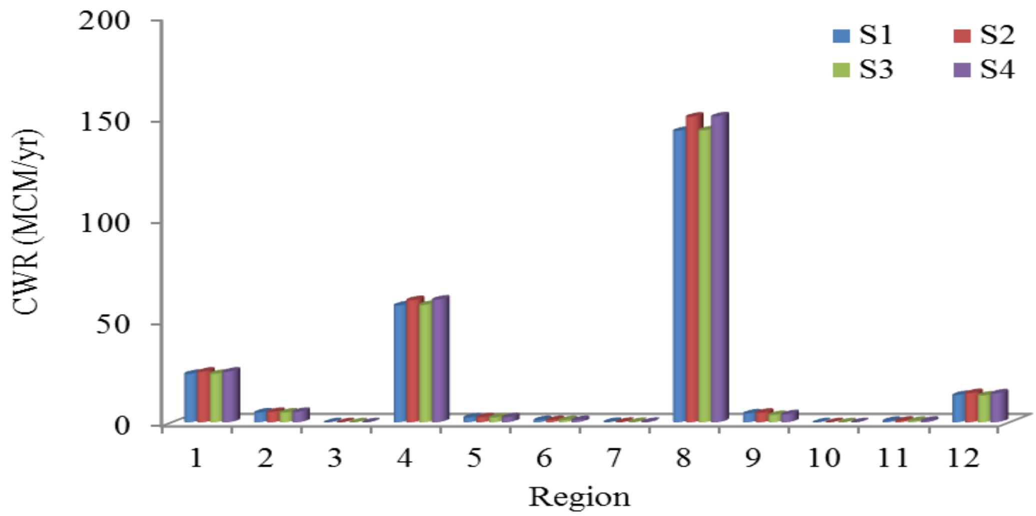


Figure 4.53: CWR in producing maize in Saudi Arabia.

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al Jouf]

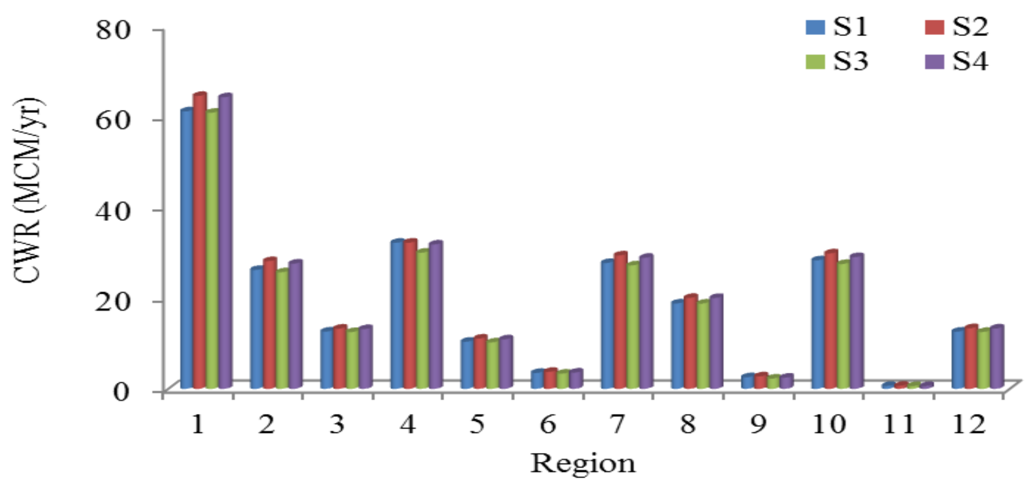


Figure 4.54: CWR in producing citrus in Saudi Arabia.

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

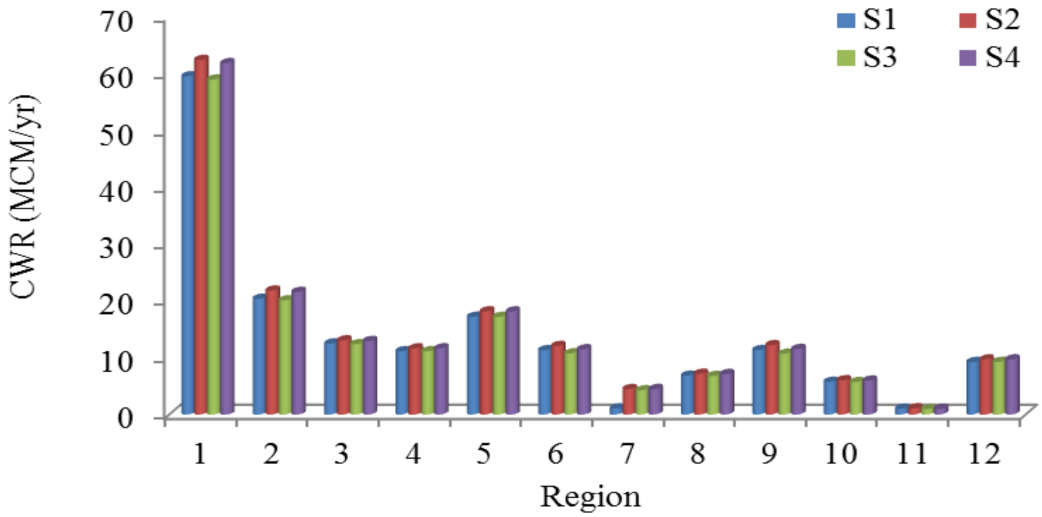


Figure 4.55: CWR in producing tomato in Saudi Arabia.

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

The main regions for producing potatoes are: Hail, Riyadh, Qaseem, Tabouk and Al-Jouf. In these regions, CWR for potatoes was predicted to be in the ranges of 48 – 51, 35 – 36, 34 – 36, 20 – 22 and 14 – 15 MCM/yr respectively. The CWR for the other regions is not significant (e.g., 0.2 – 1.5 MCM/yr) (Figure 4.56). Grapes are produced in all regions except Jazan. The CWR for grapes was predicted to be in the range of 151 – 160 MCM/yr for the S1 – S4 scenarios. The CWR for grapes in Madinah region was predicted to be the highest (47 – 50 MCM/yr), followed by Riyadh (22 – 23 MCM/yr), Al-Jouf (17 – 19 MCM/yr), Tabouk (16 - 17 MCM/yr), Qaseem and Hail (14 - 16 MCM/yr) and Makkah (10 MCM/yr). The CWR for the other regions ranges between 0.5 and 3 MCM/yr (Figure 4.57). The main regions producing millet are Jazan and Makkah, while it was not significant in the other regions (e.g, Madinah, Aseer and Al-Baha). The CWR for millet in Jazan and Makkah was predicted to be 9.8 – 10.7 and 5.2 – 5.7 MCM/yr respectively (Figure 4.58). Barley is produced in all regions. The CWR for barely was predicted to be in the range of 11 – 12 MCM/yr for the S1 – S4 scenarios. The CWR for barley in Al–Jouf and Riyadh regions was predicted to be 2.8 and 2 MCM/yr, while the CWR in the other regions was predicted to be 0.1 – 1.5 MCM/yr (Figure 4.59).

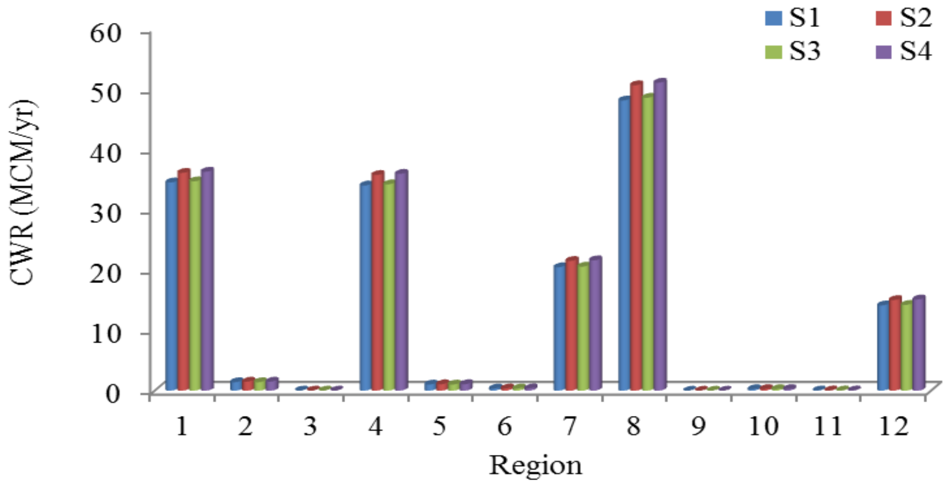


Figure 4.56: CWR in producing potatoes in Saudi Arabia.

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

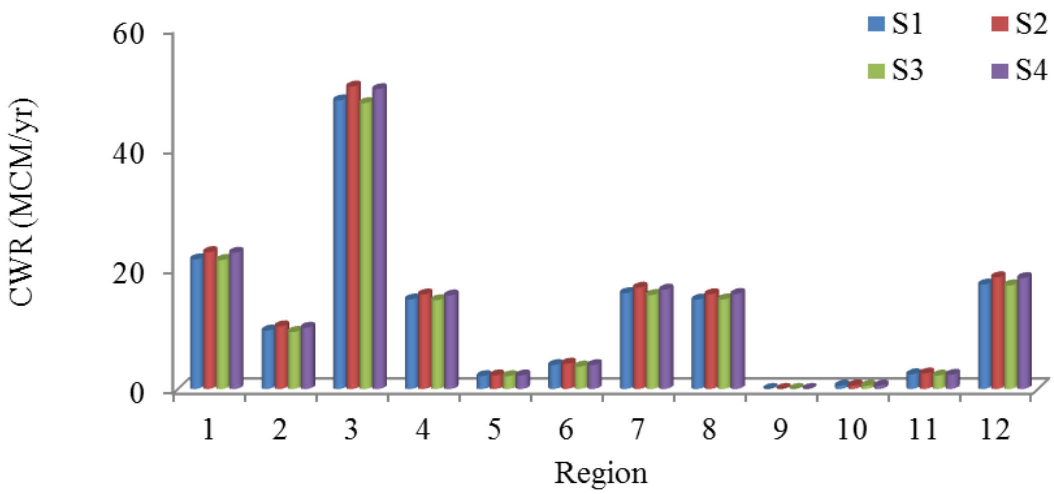


Figure 4.57: CWR in producing grapes in Saudi Arabia.

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

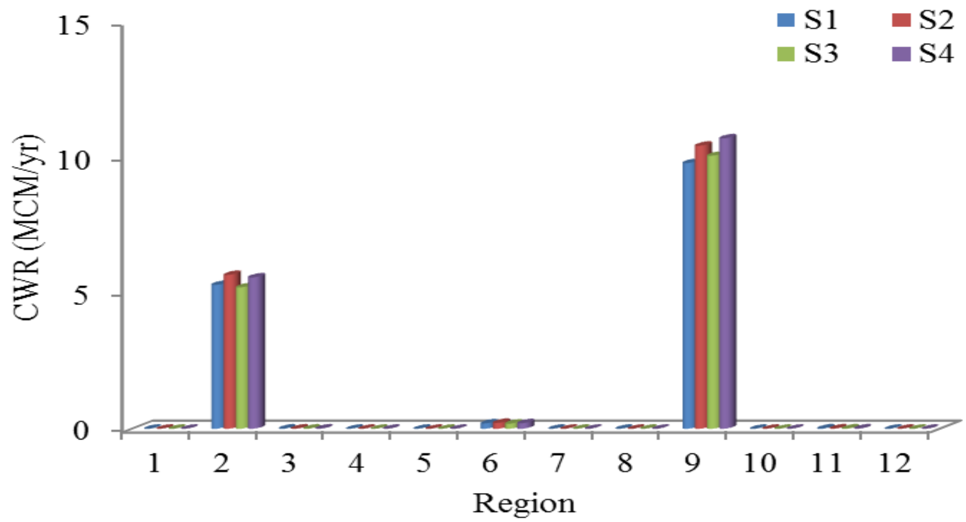


Figure 4.58: CWR in producing millet in Saudi Arabia.

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

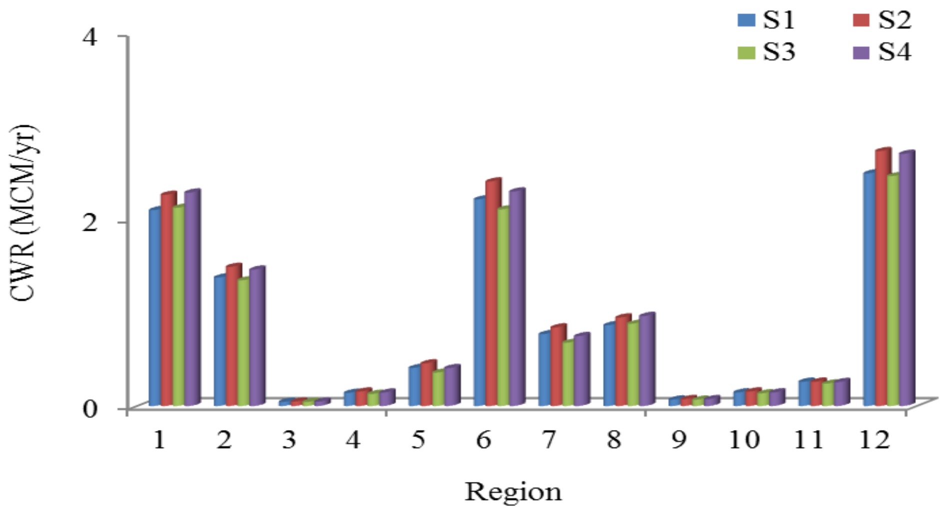


Figure 4.59: CWR in producing barley in Saudi Arabia.

[1: Riyadh, 2: Makkah, 3: Madinah, 4: Qaseem, 5: Eastern Region, 6: Aseer, 7: Tabouk, 8: Hail, 9: Jazan, 10: Najran, 11: Al-Baha, 12: Al-Jouf]

The results of this study and few past studies are presented in Table 4.14. The findings of this study are comparable to some of the past studies. Variability was observed in some cases. This variability might be attributed to several factors, including growing seasons, methods of analysis, climatic parameters and crop growth stage coefficients. Further details can be obtained in Table 4.14.

Overall, the results indicate that CWR may be highest during Apr. - Sep. and lowest during Dec. - Feb. Few crops are grown during the summer months, which might consume water at the higher rates. In addition, some crops can have their mid-season of growing stages during the summer months, which can have high values of K_c, leading to higher CWR. Shifting the mid-season of growing stages from the hot summer months may conserve significant amount of water. Chapter 5 presents sensitivity analysis focusing on such shifting for the main crops.

Table 4. 14: CWR predicted by past studies and this study for few crops in Saudi Arabia.

Study	Method	Region	Crop	CWR: Past studies (m^3/ha/season, *mm/season, **mm/yr)	CWR: This study (m^3/ha/season, *mm/season, **mm/yr)	Growing seasons: a: Past study b: This study
Mustafa et al. (1989)	FAO modified P-M	Saudi Arabia	wheat	3790 - 6740	2233-7471	a: Nov-May b: Nov-May
Al-Omran and Shalaby (1992)	Jenen-Haise equation	Eastern and Central Regions	wheat	8830	4402-6466	a: NA b: Nov-May
			maize	7510	8441-10797	a: NA b: Mar-Jun
			tomato	17030	10712-13577	a: NA b: Feb-Jul
			citrus	22590	12662-17081	a: NA b: Mar-Feb
			dates	40210	17889-23896	a: NA b: Oct-Sep
Al-Taher et al. (1992b)	Blaney and Criddle method	Ad Dawadimi (south of Qaseem)	wheat	3307- 3829	3009-5772	a: NA b: Nov-May
Al-Taher (1993 and 1994)	Jensen-Haise equation	Najd region and Yabrin oasis	wheat	4448 - 6683	3748-6466	a: NA b: Nov-May
			date palms	26440	15298-23896	a: NA b: Oct-Sep
Saif ud din et al. (2004)	Penman method	Wadi Sirhan (Al-Jouf)	Alfalfa (clover)	34864	15762-16841	a: Jan-Dec b: Mar-Feb
			potato	6522	7692-8176	a: NA b: Jan.-Apr
			wheat	6473	4078-7308	a: Jan-Apr b: Nov-May
Almisnid (2005)	FAO Penman method	Qaseem	wheat	3038	3009	a: Nov 15-Mar 24 b: Nov 15-Mar 24
			wheat	3457	3301	a: Dec 01-Apr 09 b: Dec 01-Apr 09
			wheat	3931	3863	a: Dec 15-Apr 23 b : Dec 15-Apr 23
			wheat	5188	5772	a: Jan 15-May 24 b: Jan 15-May 24
Hashim et al. (2012)	Neutron probe and lysimeter.	Makkah	millet	*727.8	*423.4	a: NA b : Jan-Apr
			wheat	*518.5	*542.9-689.4	a: NA b : Nov-May
			maize	*452.6	*778.9-828.1	a: NA b : Mar-Jun
			Alfalfa (clover)	*1922.5	*1633.1-1752.3	a: NA b : Oct-Sep
Alamoud et al. (2012)	FAO Penman method	Hafuf, Madinah, Makkah, Najran, Gaseem, Riyadh and Wadi Addwaser	date palm	* 2100 - 2829	*1789-2390	a: Jan-Dec b : Oct-Sep

*NA: Not available

CHAPTER 5

SENSITIVITY ANALYSIS

To better understand and manage CWR, sensitivity analysis was performed by shifting the growing periods for few major crops (e.g., wheat, sorghum, clover, dates, citrus and grapes). There might be a chance to reduce the CWR for these crops by shifting their growing periods and/or the mid-seasons of growing stages. The region wise analyses are presented below.

5.1 Riyadh Region

The largest area is used for cultivating clover, followed by dates and winter wheat. Dates and clover are perennial crops. The growing periods till harvesting is around one year. Their growing periods are: Dec – Nov and Oct – Sep, while the growing period for wheat is Jan. – May respectively. Sensitivity analyses were performed for clover and dates by shifting their growing periods by up to 30 days before and after the current planting dates. The growing periods for clover were considered to be: Sep 15 – Sep 14, Sep 01 – Aug 31, Oct 15 – Oct 14 and Nov 01 – Oct 31. For dates, the growing periods were assumed to be Nov 15 – Nov 14, Nov 01 – Oct 31, Dec 15 – Dec 14 and Jan 01 – Dec 31. For the growing period of Sep 15 – Sep 14, CWR for clover was predicted to be 974 - 1031 MCM/yr for S1 - S4 scenarios, representing 11 - 11.5 MCM/yr of water saving (Case I in Table 5.1a). When the growing season was assumed to be Sep 01 – Aug

31, the CWR was in the range of 948 - 1003 MCM/yr, representing 37 - 39 MCM/yr of water saving (Case II in Table 5.1a). However, the CWR for the growing period of Oct 15 – Oct 14, was predicted to be higher than the current practice, representing 8 - 9 MCM/yr of water increase (Case III in Table 5.1a). In the growing period of Nov 01 – Oct 31, CWR was predicted to be 982 - 1040 MCM/yr for S1 - S4 scenarios, representing 2 - 3 MCM/yr of water saving (Case IV in Table 5.1a).

For dates, shifts in growing periods to Nov 15 – Nov 14 and Nov 01 - Oct 31 increased CWR by 5 – 13 MCM/yr for S1 - S4 scenarios (Cases I - II in Table 5.1 b). The CWR for dates was predicted to be 1019 – 1078 MCM/yr for S1 - S4 scenarios at the growing period of Dec 15 – Dec 14. It is predicted to be lower (e.g., 1006 – 1066 MCM/yr) for S1 - S4 scenarios in the growing period of Jan 01 – Dec 31. Water conservation for dates was predicted to be 9 - 10 MCM/yr and 21 - 22 MCM/yr for these growing periods respectively (Case III - IV in Table 5.1 b).

Table 5.1c shows the sensitivity analysis for CWR in producing wheat. For a growing period of Jan 01 – May 10, CWR was predicted to be 173 - 186 MCM/yr for S1 - S4 scenarios, representing 27 - 29 MCM/yr of water saving (Case I in Table 5.1c). When the growing season was assumed to be Dec 15 – Apr 23, CWR was predicted to be 146 – 158 MCM/yr for S1 - S4 scenarios, representing 54 - 56 MCM/yr of water saving (Case II in Table 5.1c). For the growing period of Dec 01 – Apr 09, CWR was predicted to be 132 - 143 MCM/yr for S1 - S4 scenarios, representing 68 - 72 MCM/yr of water saving (Case III in Table 5.1c). The CWR for the other scenarios are also presented in Table 5.1c.

Table 5. 1: Sensitivity analysis for clover, dates and wheat in Riyadh

(a) Sensitivity analysis for CWR in producing clover

Scenario	CWR (MCM/year)					Water Conservation (MCM/year)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	*Case III	Case IV
S1	988.9	978.2	952.0	996.7	986.2	10.7	36.9	-7.8	2.7
S2	1042.0	1030.6	1003.0	1050.7	1040.2	11.4	39.0	-8.7	1.8
S3	984.8	974.1	947.8	992.5	982.1	10.7	36.9	-7.8	2.6
S4	1037.9	1026.4	998.8	1046.5	1036.1	11.5	39.0	-8.7	1.8

Current practice: Oct 01 - Sep 30; Case I: (Sep 15 - Sep 14); Case II: (Sep 01 - Aug 31); Case III: (Oct 15 – Oct 14); Case IV: (Nov 01 – Oct 31), * Negative number means an increase in the CWR.

(b) Sensitivity analysis for CWR in producing dates

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	*Case I	*Case II	Case III	Case IV
S1	1031.8	1036.5	1043.8	1022.4	1010.0	-4.7	-12.0	9.4	21.8
S2	1088.2	1093.0	1100.7	1078.4	1065.8	-4.8	-12.6	9.8	22.4
S3	1028.2	1032.9	1040.2	1018.8	1006.4	-4.7	-12.0	9.4	21.8
S4	1084.7	1089.4	1097.2	1074.8	1062.2	-4.7	-12.6	9.8	22.4

Current practice :(Dec 01 - Nov 30); Case I: (Nov 15 - Nov 14); Case II: (Nov 01 - Oct 31); Case III: (Dec 15 –Dec 14); Case IV: (Jan 01 – Dec 31), * Negative number means an increase in the CWR.

(c) Sensitivity analysis for CWR in producing wheat

Scenario	CWR (MCM/yr)						Water Conservation (MCM/yr)				
	Current Practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	Case IV	Case V
S1	199.8	172.6	146.1	131.5	120.7	117.4	27.2	53.6	68.3	79.1	82.4
S2	211.3	183.5	156.2	140.9	129.8	126.5	27.8	55.1	70.4	81.5	84.8
S3	202.8	174.9	148.1	133.2	122.3	118.7	27.9	54.7	69.5	80.4	84.0
S4	214.3	185.8	158.2	142.7	131.5	127.8	28.5	56.1	71.6	82.8	86.4

Current practice: Jan 15 – May 24; Case I: (Jan 01 – May 10); Case II: (Dec 15 – Apr 23); Case III: (Dec 01 –Apr 09); Case IV: (Nov 15 – Mar 24); Case V: (Nov 01 – Mar 10)

5.2 Makkah Region

Dates and wheat are the major crops in this region. Sensitivity analyses were performed for dates by shifting the growing periods as shown in Table 5.2a. For these growing periods, CWR was predicted to be in the range of 221 – 242 MCM/yr for S1 - S4 scenarios, representing 0.3 - 1.5 MCM/yr of water saving (Cases I - IV in Table 5.2a). For wheat, the planting dates were shifted at the interval of 15 days (Table 5.2b). The water conservation was predicted to be 0.1 – 0.7MCM/yr for the S1 – S4 scenarios (Cases I - V in Table 5.2b).

Table 5. 2: Sensitivity analysis for dates and wheat in Makkah region

(a) Sensitivity analysis for CWR in producing dates

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	Case III	Case IV
S1	225.7	224.2	224.5	224.8	225.3	1.4	1.1	0.9	0.3
S2	242.2	240.6	241.0	241.2	241.8	1.5	1.2	1.0	0.4
S3	222.3	220.8	221.1	221.4	221.9	1.4	1.1	0.9	0.3
S4	238.8	237.3	237.6	237.8	238.4	1.5	1.2	0.9	0.4

Current practice: (Aug 01 - Jul 31); Case I: (Jul 15 - Jul 14); Case II: (Jul 01 - Jun 31); Case III: (Aug 15 – Aug 14); Case IV: (Sep 01 – Aug 31)

(b) Sensitivity analysis for CWR in producing wheat

Scenario	CWR (MCM/yr)						Water Conservation (MCM/yr)				
	Current Practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	Case IV	Case V
S1	2.6	2.4	2.3	2.1	2.0	1.9	0.1	0.3	0.4	0.5	0.6
S2	2.7	2.6	2.4	2.3	2.2	2.1	0.1	0.3	0.4	0.5	0.6
S3	2.5	2.3	2.2	2.0	1.9	1.8	0.2	0.4	0.5	0.6	0.7
S4	2.7	2.5	2.3	2.2	2.1	2.0	0.2	0.4	0.5	0.6	0.7

Current practice: Jan 15 – May 24; Case I: (Jan 01 – May 10); Case II: (Dec 15 – Apr 23); Case III: (Dec 01 –Apr 09); Case IV: (Nov 15 – Mar 24); Case V: (Nov 01 – Mar 10)

5.3 Madinah Region

The most important crops in Madinah region are dates, followed by grapes and clover representing approximately 68, 11 and 9% of the total cultivated area respectively. The CWR for the current practices, shifted growing seasons and corresponding water conservation are shown in Table 5.3.

Table 5. 3: Sensitivity analysis for dates, grapes and clover in Madinah region

(a) Sensitivity analysis for CWR in producing dates

Scenario	CWR (MCM/year)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	*Case II	Case III	Case IV
S1	428.8	427.3	429.3	426.0	425.1	1.5	-0.5	2.7	3.6
S2	450.5	449.0	451.2	447.6	446.7	1.5	-0.7	3.0	3.9
S3	426.1	424.7	426.7	423.4	422.5	1.4	-0.4	2.7	3.6
S4	447.9	446.4	448.6	445.0	444.0	1.5	-0.7	3.0	3.9

Current practice: (Mar 01 - Feb 28); Case I: (Feb 15 - Feb 14); Case II: (Feb 01 - Jan 31); Case III: (Mar15 –Mar 14); Case IV: (Apr 01 – Mar 31), * Negative number means an increase in the CWR.

(b) Sensitivity analysis for CWR in producing grapes

Scenario	CWR (MCM/year)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	Case III	Case IV
S1	48.0	47.8	47.2	47.8	47.2	0.2	0.8	0.2	0.8
S2	50.3	50.1	49.5	50.1	49.5	0.2	0.8	0.2	0.8
S3	47.5	47.4	46.8	47.4	46.7	0.1	0.7	0.1	0.8
S4	49.9	49.7	49.0	49.7	49.1	0.2	0.8	0.2	0.8

Current practice: (Oct 01 - Sep 30); Case I: (Sep 15-Sep 14); Case II: (Sep 01 - Aug 31); Case III: (Oct 15 – Oct 14); Case IV: (Nov 01 – Oct 31)

(c) Sensitivity analysis for CWR in producing clover.

Scenario	CWR (MCM/year)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	*Case III	Case IV
S1	46.8	46.7	46.0	46.8	46.1	0.0	0.8	-0.1	0.6
S2	49.1	49.0	48.3	49.1	48.4	0.0	0.8	-0.1	0.6
S3	46.4	46.4	45.6	46.5	45.8	0.0	0.8	-0.1	0.6
S4	48.7	48.7	47.9	48.8	48.1	0.0	0.8	-0.1	0.6

Current practice: (Oct 01 - Sep 30); Case I: (Sep 15 - Sep 14); Case II: (Sep 01 - Aug 31); Case III: (Oct 15 –Oct 14); Case IV: (Nov 01 – Oct 31), * Negative number means an increase in the CWR.

5.4 Qaseem Region

In Qaseem region, the highest cultivated areas are used for cultivating dates, wheat and clover, representing approximately 40, 23 and 15% of the total cultivated land respectively. The CWR for the current practices, shifted growing seasons and corresponding water conservation are shown in Table 5.4.

Table 5. 4: Sensitivity analysis for dates, wheat and clover in Qaseem

(a) Sensitivity analysis for CWR in producing dates

Scenario	CWR (MCM/year)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	Case III	Case IV
S1	837.2	832.5	832.4	834.2	835.1	4.8	4.8	3.0	2.2
S2	885.5	880.5	880.7	882.1	883.1	4.9	4.8	3.4	2.4
S3	829.5	824.6	824.6	826.4	827.2	4.9	4.9	3.1	2.3
S4	877.6	872.7	872.9	874.3	875.2	5.0	4.8	3.4	2.4

Current practice: (Oct 01 - Sep 30); Case I: (Sep 15 - Sep 14); Case II: (Sep 01 - Aug 31); Case III: (Oct 15 –Oct 14); Case IV: (Nov 01 – Oct 31)

(b) Sensitivity analysis for CWR in producing wheat

Scenario	CWR (MCM/yr)						Water Conservation (MCM/yr)				
	Current Practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	Case IV	Case V
S1	131.6	109.8	88.0	75.2	68.6	70.0	21.7	43.5	56.3	63.0	61.5
S2	140.4	118.1	95.7	82.4	75.5	77.1	22.3	44.7	57.9	64.9	63.3
S3	130.7	107.6	84.7	71.1	63.9	65.2	23.1	46.0	59.7	66.8	65.5
S4	139.6	115.9	92.3	78.3	70.7	72.2	23.7	47.2	61.3	68.8	67.4

Current practice: Jan 15 – May 24; Case I: (Jan 01 – May 10); Case II: (Dec 15 – Apr 23); Case III: (Dec 01 –Apr 09); Case IV: (Nov 15 – Mar 24); Case V: (Nov 01 – Mar 10)

(c) Sensitivity analysis for CWR in producing clover

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	*Case III	Case IV
S1	252.3	251.0	245.7	254.5	252.1	1.3	6.6	-2.1	0.2
S2	266.6	265.2	259.7	268.9	266.5	1.3	6.8	-2.3	0.0
S3	249.5	248.2	242.9	251.6	249.2	1.3	6.6	-2.1	0.2
S4	263.6	262.3	256.8	265.9	263.6	1.3	6.8	-2.3	0.1

Current practice: (Oct 01 - Sep 30); Case I: (Sep 15 - Sep 14); Case II: (Sep 01 - Aug 31); Case III: (Oct 15 – Oct 14); Case IV: (Nov 01 – Oct 31), * Negative number means an increase in the CWR.

5.5 Eastern Region

In Eastern region, wheat is one of the most important cultivated crops followed by dates. Their cultivated areas are approximately 30691 and 13548 hectares, representing about 56 and 25% of the total cultivated area in the region respectively. The CWR for the current practices, shifted growing seasons and corresponding water conservation are shown in Table 5.5.

Table 5. 5: Sensitivity analysis for wheat and dates in Eastern region

(a) Sensitivity analysis for CWR in producing wheat

Scenario	CWR (MCM/yr)						Water Conservation (MCM/yr)				
	Current Practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	Case IV	Case V
S1	135.1	113.7	92.4	78.3	68.5	67.6	21.4	42.7	56.9	66.6	67.5
S2	144.7	122.7	101.0	86.5	76.6	75.8	22.1	43.7	58.2	68.2	69.0
S3	133.7	110.9	87.8	72.0	61.5	60.4	22.8	45.9	61.7	72.2	73.3
S4	143.2	119.7	96.2	80.2	69.5	68.5	23.4	47.0	62.9	73.7	74.6

Current practice: Jan 15 – May 24; Case I: (Jan 01 – May 10); Case II: (Dec 15 – Apr 23); Case III: (Dec 01 –Apr 09); Case IV: (Nov 15 – Mar 24); Case V: (Nov 01 – Mar 10)

(b) Sensitivity analysis for CWR in producing dates

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	Case III	Case IV
S1	242.4	240.6	241.4	240.6	240.6	1.7	0.9	1.7	1.8
S2	258.4	256.5	257.4	256.5	256.5	1.8	0.9	1.8	1.9
S3	239.5	237.8	238.6	237.8	237.7	1.7	0.9	1.7	1.8
S4	255.5	253.7	254.6	253.7	253.6	1.8	0.9	1.8	1.9

Current practice: (Aug 01 - Jul 31); Case I: (Jul 15 - Jul14); Case II: (Jul 01 - Jun 30); Case III: (Aug 15 – Aug 14); Case IV: (Sep 01 – Aug 31)

5.6 Aseer Region

In Aseer region, the largest cultivated land is occupied by dates, wheat, sorghum and clover. Their cultivated areas are: 5075, 3155, 2173 and 1419 hectares representing approximately 31, 19, 13 and 9% of the total cultivated land, respectively. The CWR for the current practices, shifted growing seasons and corresponding water conservation are shown in Table 5.6.

Table 5. 6: Sensitivity analysis for dates, wheat, sorghum and clover in Aseer region

(a) Sensitivity analysis for CWR in producing dates

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	Case III	Case IV
S1	77.6	77.1	77.2	77.3	77.6	0.6	0.5	0.4	0.1
S2	82.8	82.3	82.5	82.3	82.6	0.5	0.4	0.5	0.2
S3	75.0	74.4	74.5	74.6	74.9	0.6	0.5	0.4	0.1
S4	80.2	79.6	79.8	79.6	79.9	0.5	0.4	0.5	0.2

Current practice: (Aug 01 - Jul 31); Case I: (Jul 15 - Jul14); Case II: (Jul 01 - Jun 30); Case III: (Aug 15 – Aug 14); Case IV: (Sep 01 – Aug 31)

(b) Sensitivity analysis for CWR in producing wheat

Scenario	CWR (MCM/yr)						Water Conservation (MCM/yr)				
	Current Practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	Case IV	Case V
S1	13.5	12.8	12.2	11.8	11.8	12.1	0.7	1.3	1.6	1.6	1.4
S2	14.7	14.0	13.3	12.9	12.9	13.2	0.7	1.4	1.7	1.8	1.5
S3	13.4	12.6	11.9	11.5	11.5	11.6	0.8	1.5	1.9	1.9	1.8
S4	14.6	13.8	13.0	12.6	12.5	12.7	0.8	1.6	2.0	2.1	1.9

Current practice: Jan 15 – May 24; Case I: (Jan 01 – May 10); Case II: (Dec 15 – Apr 23); Case III: (Dec 01 –Apr 09); Case IV: (Nov 15 – Mar 24); Case V: (Nov 01 – Mar 10)

(c) Sensitivity analysis for CWR in producing sorghum

Scenario	CWR (MCM/yr)						Water Conservation (MCM/yr)				
	Current Practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	*Case IV	Case V
S1	10.2	9.8	7.7	7.1	10.4	10.0	0.4	2.5	3.1	-0.2	0.2
S2	10.7	10.1	8.4	7.8	11.2	10.9	0.6	2.3	2.9	-0.6	-0.2
S3	10.1	9.9	7.7	7.1	9.5	9.0	0.2	2.4	3.0	0.6	1.1
S4	10.6	10.2	8.4	7.8	10.3	9.9	0.4	2.2	2.8	0.3	0.7

Current practice: (Apr 15 - Aug 17); Case I: (Apr 01 - Aug 03); Case II: (Feb 01 - Jun 05); Case III: (Jan 15 –May 19); Case IV: (Jul 01 – Nov 02); Case V: (Jul 15 - Nov 16), * Negative number means an increase in the CWR

(d) Sensitivity analysis for CWR in producing clover

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	*Case III	Case IV
S1	16.3	16.2	15.9	16.5	16.3	0.1	0.4	-0.2	0.0
S2	17.4	17.3	17.0	17.6	17.4	0.1	0.4	-0.2	0.0
S3	15.6	15.5	15.2	15.7	15.6	0.1	0.4	-0.1	0.0
S4	16.7	16.6	16.2	16.8	16.6	0.1	0.4	-0.1	0.0

Current practice: (Oct 01 - Sep 30); Case I: (Sep 15 - Sep 14); Case II: (Sep 01 - Aug 31); Case III: (Oct 15 –Oct 14); Case IV: (Nov 01 – Oct 31), * Negative number means an increase in the CWR

5.7 Tabouk Region

The largest areas are used for cultivating wheat, clover and dates. Their corresponding growing seasons are: Jan. – May, Oct. – Sep. and Oct. – Sep. respectively. The CWR for the current practices and shifted growing seasons for these crops are shown in Table 5.7.

Table 5. 7: Sensitivity analysis for wheat, clover and dates in Tabouk region

(a) Sensitivity analysis for CWR in producing wheat

Scenario	CWR (MCM/yr)						Water Conservation (MCM/yr)				
	Current Practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	Case IV	Case V
S1	117.1	102.8	85.7	73.3	63.2	58.2	14.3	31.4	43.8	54.0	58.9
S2	124.0	109.3	91.6	78.9	68.5	63.5	14.7	32.4	45.2	55.5	60.5
S3	114.4	98.7	80.8	67.8	57.2	52.1	15.7	33.6	46.6	57.2	62.3
S4	121.3	105.2	86.7	73.3	62.5	57.5	16.1	34.7	48.0	58.8	63.8

Current practice: Jan 15 – May 24; Case I: (Jan 01 – May 10); Case II: (Dec 15 – Apr 23); Case III: (Dec 01 –Apr 09); Case IV: (Nov 15 – Mar 24); Case V: (Nov 01 – Mar 10)

(b) Sensitivity analysis for CWR in producing clover

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	*Case III	Case IV
S1	150.3	149.5	146.3	150.9	148.6	0.8	4.0	-0.7	1.6
S2	159.1	158.2	154.8	159.9	157.6	0.9	4.3	-0.9	1.5
S3	147.7	146.9	143.7	148.4	146.1	0.8	4.0	-0.7	1.6
S4	156.5	155.6	152.2	157.3	154.9	0.9	4.3	-0.9	1.5

Current practice: (Oct 01 - Sep 30); Case I: (Sep 15 - Sep 14); Case II: (Sep 01 - Aug 31); Case III: (Oct 15 –Oct 14); Case IV: (Nov 01 – Oct 31), * Negative number means an increase in the CWR.

(c) Sensitivity analysis for CWR in producing dates

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	Case III	Case IV
S1	46.1	45.9	45.9	45.8	45.8	0.2	0.2	0.3	0.3
S2	48.9	48.6	48.7	48.6	48.5	0.2	0.2	0.3	0.3
S3	45.4	45.2	45.3	45.2	45.1	0.2	0.2	0.3	0.3
S4	48.2	48.0	48.0	47.9	47.9	0.2	0.2	0.3	0.3

Current practice: (Oct 01 - Sep 30); Case I: (Sep 15 - Sep 14); Case II: (Sep 01 - Aug 31); Case III: (Oct 15 –Oct 14); Case IV: (Nov 01 – Oct 31)

5.8 Hail Region

The most important cultivated crop in Hail is wheat followed by dates, and clover. Their cultivated areas are: 23558, 18743 and 7127 hectares, representing 30, 24 and 9% of the total cultivated area respectively. The CWR for the current practices, shifted growing seasons and corresponding water conservation are shown in Table 5.8.

Table 5. 8: Sensitivity analysis for wheat, dates and clover in Hail region

(a) Sensitivity analysis for CWR in producing wheat

Scenario	CWR (MCM/yr)						Water Conservation (MCM/yr)				
	Current Practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	Case IV	Case V
S1	125.5	108.3	90.0	77.8	65.2	56.5	17.2	35.5	47.7	60.3	69.0
S2	133.8	116.0	97.3	84.5	71.1	62.3	17.8	36.5	49.3	62.7	71.5
S3	129.1	111.9	92.3	79.7	66.6	57.4	17.1	36.8	49.4	62.4	71.7
S4	137.4	119.6	99.4	86.4	72.6	63.3	17.8	37.9	50.9	64.8	74.1

Current practice: Jan 15 – May 24; Case I: (Jan 01 – May 10); Case II: (Dec 15 – Apr 23); Case III: (Dec 01 –Apr 09); Case IV: (Nov 15 – Mar 24); Case V: (Nov 01 – Mar 10)

(b) Sensitivity analysis for CWR in producing dates

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	Case III	Case IV
S1	367.2	365.3	366.2	365.3	365.8	1.9	1.0	1.9	1.3
S2	390.3	388.3	389.3	388.2	388.8	2.0	0.9	2.1	1.5
S3	367.0	365.1	366.0	365.1	365.6	1.9	1.0	1.9	1.3
S4	390.1	388.1	389.2	388.0	388.6	2.0	0.9	2.1	1.5

Current practice: (Oct 01 - Sep 30); Case I: (Sep 15 - Sep 14); Case II: (Sep 01 - Aug 31); Case III: (Oct 15 –Oct 14); Case IV: (Nov 01 – Oct 31)

(c) Sensitivity analysis for CWR in producing clover

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	*Case III	Case IV
S1	112.7	112.0	109.3	113.6	112.4	0.7	3.4	-0.9	0.3
S2	119.6	118.8	115.9	120.6	119.4	0.8	3.6	-1.0	0.2
S3	112.8	112.0	109.4	113.7	112.5	0.7	3.4	-0.9	0.3
S4	119.6	118.8	116.0	120.6	119.4	0.8	3.6	-1.0	0.2

Current practice: (Oct 01 - Sep 30); Case I: (Sep 15 - Sep 14); Case II: (Sep 01 - Aug 31); Case III: (Oct 15 –Oct 14); Case IV: (Nov 01 – Oct 31), * Negative number means an increase in the CWR.

5.9 Jazan Region

Sorghum is the most important crop in Jazan. It covers approximately 83618 hectares of the cultivatewsyd lands, representing about 92% of the total cultivated land in the region. While, the corresponding growing seasons for sorghum are in the early of April, early of July and/or from the mid of Jan. to the mid of Feb., this study assumed the corresponding growing period is Apr. - Aug. The CWR for the current practices, shifted growing seasons and corresponding water conservation are shown in Table 5.9.

Table 5. 9: Sensitivity analysis for CWR in producing sorghum in Jazan region

Scenario	CWR (MCM/yr)						Water Conservation (MCM/yr)				
	Current Practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	Case IV	Case V
S1	525.4	518.1	456.6	430.8	490.6	467.8	7.3	68.7	94.6	34.8	57.5
S2	562.8	553.3	484.6	457.8	532.4	508.8	9.5	78.2	105.0	30.4	54.0
S3	523.8	524.0	465.3	440.4	372.9	334.7	-0.3	58.4	83.4	150.8	189.1
S4	561.1	559.2	493.4	467.4	414.7	375.8	1.8	67.6	93.7	146.4	185.3

Current practice: (Apr 15 - Aug 17); Case I: (Apr 01 - Aug 03); Case II: (Feb 01 - Jun 05); Case III: (Jan 15 –May 19); Case IV: (Jul 01 – Nov 02); Case V: (Jul 15 - Nov 16)

5.10 Najran Region

The total cultivated areas in Najran region are approximately 9450 hectares. Approximately 3367, 1914, 1833 and 763 hectares of this cultivated land are used for producing dates, clover, citrus and wheat. The CWR for the current practices, shifted growing seasons and corresponding water conservation are shown in Table 5.10.

Table 5. 10: Sensitivity analysis for dates, clover, citrus and wheat in Najran region

(a) Sensitivity analysis for CWR in producing dates

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	Case III	Case IV
S1	72.0	71.5	71.8	71.6	**71.7**	0.5	0.2	0.4	0.3
S2	75.8	75.3	75.6	75.3	75.5	0.5	0.2	0.5	0.3
S3	70.5	70.0	70.3	70.1	70.2	0.5	0.2	0.4	0.3
S4	74.3	73.8	74.1	73.8	74.0	0.5	0.2	0.5	0.3

Current practice: (Mar 01 - Feb 28); Case I: (Feb 15 - Feb 14); Case II: (Feb 01 - Jan 31); Case III: (Mar15 –Mar 14); Case IV: (Apr 01 – Mar 31)

(b) Sensitivity analysis for CWR in producing clover

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	Case III	Case IV
S1	32.1	32.0	31.3	32.1	31.7	0.1	0.8	0.0	0.4
S2	33.7	33.6	32.9	33.7	33.3	0.1	0.8	0.0	0.4
S3	31.2	31.1	30.5	31.2	30.8	0.1	0.8	0.0	0.4
S4	32.9	32.8	32.1	32.9	32.5	0.1	0.8	0.0	0.4

Current practice: (Oct 01 - Sep 30); Case I: (Sep 15 - Sep 14); Case II: (Sep 01 - Aug 31); Case III: (Oct 15 –Oct 14); Case IV: (Nov 01 – Oct 31).

(c) Sensitivity analysis for CWR in producing citrus

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	Case III	Case IV
S1	28.3	28.1	28.2	28.1	28.3	0.2	0.1	0.2	0.0
S2	29.9	29.6	29.8	29.7	29.8	0.2	0.1	0.2	0.1
S3	27.5	27.3	27.4	27.3	27.5	0.2	0.1	0.2	0.0
S4	29.1	28.8	28.9	28.9	29.0	0.2	0.1	0.2	0.1

Current practice: (Oct 01 - Sep 30); Case I: (Sep 15 - Sep 14); Case II: (Sep 01 - Aug 31); Case III: (Oct 15 –Oct 14); Case IV: (Nov 01 – Oct 31)

(d) Sensitivity analysis for CWR in producing wheat

Scenario	CWR (MCM/yr)						Water Conservation (MCM/yr)				
	Current Practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	Case IV	Case V
S1	4.7	4.4	4.0	3.8	3.8	3.9	0.4	0.7	0.9	1.0	0.9
S2	5.0	4.7	4.3	4.1	4.0	4.1	0.4	0.7	0.9	1.0	0.9
S3	4.6	4.2	3.8	3.6	3.6	3.6	0.4	0.8	1.0	1.1	1.0
S4	4.9	4.5	4.1	3.9	3.8	3.9	0.4	0.8	1.0	1.1	1.0

Current practice: Jan 15 – May 24; Case I: (Jan 01 – May 10); Case II: (Dec 15 – Apr 23); Case III: (Dec 01 –Apr 09); Case IV: (Nov 15 – Mar 24); Case V: (Nov 01 – Mar 10)

5.11 Al-Baha Region

Dates and wheat are the main crops in the Al-Baha. The CWR for the current practices, shifted growing seasons and corresponding water conservation are shown in Table 5.11.

Table 5. 11: Sensitivity analysis for dates and wheat in Al-Baha region

(a) Sensitivity analysis for CWR in producing dates

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case IV	Case I	Case II	Case III	Case IV
S1	28.2	28.0	28.1	28.0	28.1	0.2	0.1	0.2	0.1
S2	29.8	29.6	29.7	29.6	29.7	0.2	0.1	0.2	0.1
S3	26.7	26.5	26.6	26.5	26.6	0.2	0.1	0.2	0.1
S4	28.3	28.1	28.2	28.1	28.2	0.2	0.1	0.2	0.1

Current practice: (Aug 01 - Jul 31); Case I: (Jul 15 - Jul 14); Case II: (Jul 01 - Jun 30); Case III: (Aug 15 – Aug 14); Case IV: (Sep 01 – Aug 31)

(b) Sensitivity analysis for CWR in producing wheat

Scenario	CWR (MCM/yr)						Water Conservation (MCM/yr)				
	Current Practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	Case IV	Case V
S1	2.6	2.4	2.2	2.1	2.0	2.0	0.2	0.4	0.5	0.6	0.6
S2	2.8	2.6	2.4	2.2	2.1	2.1	0.2	0.4	0.5	0.6	0.7
S3	2.7	2.5	2.3	2.1	2.0	1.9	0.2	0.4	0.6	0.7	0.7
S4	2.8	2.6	2.4	2.2	2.1	2.1	0.2	0.4	0.6	0.7	0.7

Current practice: Jan 15 – May 24; Case I: (Jan 01 – May 10); Case II: (Dec 15 – Apr 23); Case III: (Dec 01 –Apr 09); Case IV: (Nov 15 – Mar 24); Case V: (Nov 01 – Mar 10)

5.12 Al-Jouf Region

The largest areas in Al-Jouf are used for cultivating winter wheat (65162 hectares) followed by clover (11908 hectares) and dates (5470 hectares). The CWR for the current practices, shifted growing seasons and corresponding water conservation are shown in Table 5.12.

Table 5. 12: Sensitivity analysis for wheat, clover and dates in Al-Jouf region

(a) Sensitivity analysis for CWR in producing wheat

Scenario	CWR (MCM/yr)						Water Conservation (MCM/yr)				
	Current Practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	Case IV	Case V
S1	476.2	417.0	347.5	301.1	265.7	248.7	59.2	128.7	175.1	210.5	227.5
S2	507.1	447.1	375.2	326.6	289.7	272.1	59.9	131.9	180.5	217.4	235.0
S3	479.5	417.7	347.4	300.0	264.2	247.0	61.8	132.1	179.5	215.3	232.4
S4	510.3	447.8	375.1	325.5	288.1	270.4	62.6	135.3	184.9	222.2	240.0

Current practice: Jan 15 – May 24; Case I: (Jan 01 – May 10); Case II: (Dec 15 – Apr 23); Case III: (Dec 01 –Apr 09); Case IV: (Nov 15 – Mar 24); Case V: (Nov 01 – Mar 10)

(b) Sensitivity analysis for CWR in producing clover

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case V	*Case I	*Case II	Case III	Case V
S1	187.7	193.8	199.6	184.6	180.1	-6.1	-11.9	3.1	7.6
S2	200.6	206.9	212.8	197.4	192.7	-6.3	-12.2	3.2	7.9
S3	186.6	192.8	198.5	183.5	179.1	-6.1	-11.9	3.1	7.6
S4	199.6	205.9	211.8	196.4	191.6	-6.3	-12.2	3.2	7.9

Current Practice: (Mar 01 – Feb 28); Case I: (Feb 15-Feb 14); Case II: (Feb 01-Jan 31); Case III: (Mar 15-Mar 14); Case V: (Apr 01-Mar 31); * Negative number means an increase in the CWR.

(c) Sensitivity analysis for CWR in producing dates

Scenario	CWR (MCM/yr)					Water Conservation (MCM/yr)			
	Current Practice	Case I	Case II	Case III	Case V	Case I	Case II	Case III	Case V
S1	128.9	128.5	128.9	128.6	129.4	0.4	0.0	0.3	-0.6
S2	137.1	136.6	137.0	136.8	137.6	0.5	0.1	0.3	-0.6
S3	128.4	128.0	128.4	128.2	129.0	0.4	0.0	0.3	-0.5
S4	136.6	136.1	136.5	136.3	137.1	0.5	0.1	0.3	-0.6

Current Practice: (Apr 01-Mar 31); Case I: (: Mar 15-Mar 14); Case II: (Mar 01-Feb 28); Case III: (Apr 15-Apr 14); Case V: (May 01-Apr 30); * Negative number means an increase in the CWR.

By shifting the growing periods for wheat, dates, clover, sorghum, citrus and grapes (Table 5.13), total water conservation was estimated to be 732, 750, 886 and 904 MCM/yr for the S1, S2, S3 and S4 scenarios, respectively. However, water conservation for wheat was predicted to be the highest (572 – 612 MCM/yr), representing approximately 68 - 78% from the total water conservation for the S1 - S4 scenarios respectively (Table 5.14). The remaining of water savings were predicted to be about 61 – 64, 37 – 39, 57 – 192, 0.80 – 0.81 and 0.23 – 0.24 MCM/yr for clover, dates, sorghum, grapes and citrus for the S1 – S4 scenarios respectively (Table 5.15).

Table 5. 13: CWR for each region in Saudi Arabia before and after shifting the growing periods for selected crops.

Regions	Shifted Crops	CWR (MCM/yr) Before Shifting in Each Scenario				CWR (MCM/yr) After shifting in Each Scenario				Water Conservation (MCM/year)			
		S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Riyadh	wheat, clover, dates	2802.5	2950.9	2796.9	2945.4	2661.4	2804.7	2654.2	2797.6	141.1	146.2	142.7	147.8
Makkah	dates, wheat	402.3	430.6	397.5	425.8	400.3	428.5	395.4	423.6	2.0	2.1	2.1	2.2
Madinah	dates, grapes, clover	558.0	586.0	554.3	582.4	552.8	580.5	549.1	576.9	5.2	5.5	5.2	5.5
Qaseem	wheat, clover, dates	1425.9	1505.2	1412.6	1493.6	1351.5	1428.7	1334.3	1413.2	74.4	76.5	78.3	80.4
Eastern Region	wheat, dates	485.0	516.9	480.2	511.9	415.7	446.0	405.1	435.4	69.3	70.9	75.1	76.5
Aseer	wheat, dates, clover, sorghum	145.6	155.3	141.0	150.6	139.9	149.7	135.1	144.8	5.7	5.6	5.9	5.8
Tabouk	wheat, clover, dates	390.6	413.4	383.8	406.6	327.4	348.3	317.2	338.2	63.2	65.1	66.6	68.4
Hail	wheat, clover, dates	867.3	919.0	871.4	923.0	793.0	841.8	794.4	843.2	74.3	77.2	77.0	79.8
Jazan	sorghum	574.3	615.3	571.0	611.8	516.8	561.3	381.9	426.5	57.5	54.0	189.1	185.3
Najran	wheat, clover, dates, citrus	150.4	158.2	147.1	154.9	147.9	155.7	144.5	152.3	2.5	2.5	2.6	2.6
Al-Baha	wheat, dates	38.8	41.0	36.9	39.1	38.0	40.1	36.0	38.2	0.8	0.9	0.9	0.9
Al-Jouf	wheat, dates, clover	872.7	929.8	874.1	931.4	637.2	686.4	633.7	683.0	235.5	243.4	240.4	248.4
Total		8713.4	9221.6	8666.9	9176.4	7981.9	8471.7	7781.0	8272.8	731.5	749.9	885.9	903.6

Table 5. 14: CWR for each region in Saudi Arabia before and after shifting the growing periods for wheat.

Regions	Growing Periods		CWR in Each Scenario (MCM/yr)								Water Conservation (MCM/yr)			
			Before Shifting				After Shifting							
	Current	Shifted	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Riyadh	Jan 15 - May 24	Nov 01 - Mar 10	2802.5	2950.9	2796.9	2945.4	2720.1	2866.1	2712.9	2859.0	82.4	84.8	84.0	86.4
Makkah	Jan 15 - May 24	Nov 01 - Mar 10	402.3	430.6	397.5	425.8	401.7	430.0	396.8	425.1	0.6	0.6	0.7	0.7
Madinah	Jan 15 - May 24	-	558.0	586.0	554.3	582.4	558.0	586.0	554.3	582.4	-	-	-	-
Qaseem	Jan 15 - May 24	Nov 15 - Mar 24	1425.9	1505.2	1412.6	1493.6	1362.9	1440.3	1345.8	1424.8	63.0	64.9	66.8	68.8
Eastern Region	Jan 15 - May 24	Nov 01 - Mar 10	485.0	516.9	480.2	511.9	417.5	447.9	406.9	437.3	67.5	69.0	73.3	74.6
Aseer	Jan 15 - May 24	Nov 15 - Mar 24	145.6	155.3	141.0	150.6	144.0	153.5	139.1	148.5	1.6	1.8	1.9	2.1
Tabouk	Jan 15 - May 24	Nov 01 - Mar 10	390.6	413.4	383.8	406.6	331.7	352.9	321.5	342.8	58.9	60.5	62.3	63.8
Hail	Jan 15 - May 24	Nov 01 - Mar 10	867.3	919.0	871.4	923.0	798.3	847.5	799.7	848.9	69.0	71.5	71.7	74.1
Jazan	-	-	574.3	615.3	571.0	611.8	574.3	615.3	571.0	611.8	-	-	-	-
Najran	Jan 15 - May 24	Nov 15 - Mar 24	150.4	158.2	147.1	154.9	149.4	157.2	146.0	153.8	1.0	1.0	1.1	1.1
Al-Baha	Jan 15 - May 24	Nov 01 - Mar 10	38.8	41.0	36.9	39.1	38.2	40.3	36.2	38.4	0.6	0.7	0.7	0.7
Al-Jouf	Jan 15 - May 24	Nov 01 - Mar 10	872.7	929.8	874.1	931.4	645.2	694.8	641.7	691.4	227.5	235.0	232.4	240.0
Total			8713.4	9221.6	8666.9	9176.4	8141.3	8631.8	8072.0	8564.1	572.1	589.8	594.9	612.3

Table 5. 15: Water Conservation by shifting the growing periods for several crops under different scenarios in Saudi Arabia

Shifted Crops	Total Water Conservation (MCM/year)				Percentages (%)			
	S1	S2	S3	S4	S1	S2	S3	S4
Wheat	572.1	589.8	594.9	612.3	78.2	78.6	67.1	67.8
Dates	37.3	38.6	37.4	38.6	5.1	5.1	4.2	4.3
Clover	60.5	63.6	60.5	63.6	8.3	8.5	6.8	7.0
Sorghum	60.6	56.9	192.1	188.1	8.3	7.6	21.7	20.8
Grapes	0.8	0.8	0.8	0.8	0.1	0.1	0.1	0.1
Citrus	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0
Total	731.5	749.9	885.9	903.6	100.0	100.0	100.0	100.0

An effort was given to understand the values of water conservation in context to wheat production. The increase in CWR was estimated to be in the range of 463 – 508 MCM/yr from 2011 to 2050. Assuming linear increase from 2011 to 2050, increase in CWR was estimated to be in the range of 11.9 - 13 MCM/yr from 2011. Approximately 2430 m^3 of water is needed to produce 1 ton of wheat [4], meaning that the increase in CWR is equivalent to 4886 - 5362 tons of wheat per year from 2011. If water supply is maintained at the same level, wheat productions may need to be reduced by approximately 4886 - 5360 tons per year. In Saudi Arabia, the yield of wheat production is approximately 5.4 - 5.7 tons/hectare, meaning that 857 – 993 hectares of agricultural land has to be abandoned from producing wheat every year.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

Saudi Arabia is an arid country with low annual rainfall and limited groundwater reserves, while significant amounts of crops are produced by the non-renewable groundwater reserves. However, groundwater reserves may not be adequate to provide continuous support for such type of cultivation on long-term basis. Further, effects of climate change may impose additional pressure to the availability of water sources and water demands in the agricultural sector. This study investigated possible implications of climate change on CWR in Saudi Arabia. Changes in CWR from 2011 to 2050 in each region of Saudi Arabia were predicted. Four scenarios: (i) CWR at current state of temperature and rainfall (S1); (ii) CWR at the changed temperature in 2050 and current state of rainfall (S2); (iii) CWR at the changed rainfall in 2050 and current state of temperature (S3); and (iv) CWR at the changed temperature and changed rainfall in 2050 (S4) were investigated.

The major crops in Saudi Arabia are wheat, dates, clover and vegetables, while these crops are produced in different growing seasons under variable climatic conditions. The study indicated that ET_o was in the range of 2.6 – 10.9 mm/day in 2011, which has been predicted to be in the range of 2.8 – 11.5 mm/day in 2050. Overall, approximately 6% increase in ET_o from 2011 to 2050 was predicted. CWR was predicted to be 8713 – 9221 MCM/yr for S1-S4 scenarios, indicating an increase of 463 - 508 MCM/yr of water demands. This represents 5.3 – 6% increase from 2011 to 2050 for the same level of crop productions. Increase in CWR for the same level of agricultural productions can pose an increased stress on the non-renewable groundwater resources in Saudi Arabia. Assuming that the increase in temperature from 2011 to 2050 follows linear pattern, CWR can be increased at the rate of 11.9 – 13 MCM/yr. This study confirmed that wheat is the third highest consumer of water in the Kingdom after dates and clover. The results of sensitivity analyses show that the early planting of wheat may conserve significant amount of water. However, change in the planting dates cannot be performed in a straight-forward way. Any change in planting dates needs to be evaluated with respect to crop yields, feasibility and market values. Better understanding is warranted on these factors prior to making such a decision. The following are recommended for future study:

- Understand the effects of shifting of crop growing periods with respect to crop yields, feasibility and market values.
- Minimize water loss from the agricultural activities.
- Extend the green houses cultivated areas especially for vegetables production to reduce and control the CWR.
- Evaluate the reuse of treated wastewater for agricultural purposes to compensate the effects of climate change.

Despite a number of limitations, this study sheds light on the possible implications of climate change on crop water requirements and its direct and indirect effects on water resources management. This research indicates the possibility of scheduling and/or shifting crop growing periods for few crops in some regions in Saudi Arabia.

APPENDIX (A): CWR for crops in all regions in Saudi Arabia

Table A.1: CWR for different crops under various scenarios in Riyadh region

(a) S1 scenario (current temperature and rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	26.8	81.4	178.0	232.9	127.5	-	-	-	-	-	-	-	646.6	30896	199.8
sorghum	-	-	-	-	-	-	112.7	253.9	264.0	163.0	5.3	-	798.9	1037	8.3
Maize	-	-	-	30.5	211.8	412.3	362.9	62.2	-	-	-	-	1079.7	2212	23.9
Barley	110.8	92.0	10.0	-	-	-	-	-	-	-	21.3	88.3	322.4	652	2.1
Tomato	-	-	-	4.8	160.7	279.6	386.2	351.6	174.8	-	-	-	1357.7	4383	59.5
Potato	-	2.2	65.9	197.1	325.6	347.2	63.2	-	-	-	-	-	1001.2	3446	34.5
Other vegetables	-	-	-	5.6	198.0	333.0	351.1	19.9	-	-	-	-	907.6	40879	371.0
Clover	30.7	35.4	104.4	194.4	270.8	323.1	326.5	297.8	243.4	76.0	41.4	30.3	1974.2	50090	988.9
Dates	83.0	91.9	130.0	175.6	275.0	335.5	339.0	309.4	261.9	197.2	109.9	81.2	2389.6	43178	1031.8
Citrus	59.5	66.5	94.3	145.7	209.8	252.4	229.8	209.6	176.3	131.6	74.2	58.4	1708.1	3582	61.2
Grapes	20.3	24.0	28.0	39.3	134.5	272.0	294.3	268.6	227.4	168.7	67.6	20.1	1564.8	1378	21.6
Total	331.1	393.4	610.6	1025.9	1913.7	2555.1	2465.7	1773.0	1347.8	736.5	319.7	278.3	13750.8	181733	2802.5

(b) S2 scenario (changed temperature in 2050 and current rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	29.0	87.4	188.9	245.7	132.9	-	-	-	-	-	-	-	683.9	30896	211.3
sorghum	-	-	-	-	-	-	118.4	266.8	280.0	174.6	5.7	-	845.5	1037	8.8
Maize	-	-	-	33.0	220.4	429.0	380.4	65.3	-	-	-	-	1128.1	2212	25.0
Barley	119.3	98.6	11.0	-	-	-	-	-	-	-	23.3	95.3	347.5	652	2.3
Tomato	-	-	-	5.0	167.6	291.2	405.0	369.6	185.2	-	-	-	1423.6	4383	62.4
Potato	-	2.4	70.8	208.2	338.7	361.3	66.1	-	-	-	-	-	1047.5	3446	36.1
Other vegetables	-	-	-	5.9	206.3	346.7	368.3	20.9	-	-	-	-	948.1	40879	387.6
Clover	33.7	38.4	111.3	205.2	281.6	336.2	342.3	313.0	258.3	81.8	45.1	33.3	2080.2	50090	1042.0
Dates	89.6	98.7	138.5	185.8	285.4	348.2	354.6	324.5	277.4	211.3	118.5	87.8	2520.3	43178	1088.2
Citrus	64.2	71.3	100.4	153.9	217.9	262.1	241.3	220.8	187.4	141.3	80.2	63.0	1803.8	3582	64.6
Grapes	22.5	26.2	30.8	42.6	140.0	282.7	308.2	282.0	241.1	180.9	73.0	22.3	1652.3	1378	22.8
Total	358.3	423.0	651.7	1085.3	1990.8	2657.4	2584.6	1862.9	1429.4	789.9	345.8	301.7	14480.8	181733	2950.9

Table A.1: continued

(c) S3 scenario (changed rainfall in 2050 and current temperature)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	24.9	87.6	182.3	234.3	127.2	-	-	-	-	-	-	-	656.3	30896	202.8
sorghum	-	-	-	-	-	-	113.0	250.2	251.4	162.6	5.3	-	782.5	1037	8.1
Maize	-	-	-	31.2	211.5	412.4	363.1	61.5	-	-	-	-	1079.7	2212	23.9
Barley	106.4	98.1	11.7	-	-	-	-	-	-	-	22.8	87.3	326.3	652	2.1
Tomato	-	-	-	4.8	160.4	279.7	386.5	347.9	165.7	-	-	-	1345.0	4383	59.0
Potato	-	2.2	70.2	198.6	325.2	347.3	63.3	-	-	-	-	-	1006.8	3446	34.7
Other vegetables	-	-	-	5.6	197.7	333.0	351.4	19.9	-	-	-	-	907.6	40879	371.0
Clover	26.3	41.5	108.7	195.8	270.4	323.2	326.8	294.1	230.8	75.6	43.5	29.3	1966.0	50090	984.8
Dates	78.5	98.0	134.3	177.0	274.6	335.6	339.3	305.7	249.3	196.8	112.0	80.2	2381.3	43178	1028.2
Citrus	55.1	72.6	98.6	147.2	209.5	252.5	230.0	205.9	163.7	131.1	76.3	57.4	1699.9	3582	60.9
Grapes	15.9	30.0	32.3	40.7	134.1	272.1	294.6	264.9	214.8	168.2	69.7	19.1	1556.4	1378	21.4
Total	307.1	430.0	638.1	1035.2	1910.6	2555.8	2468.0	1750.1	1275.7	734.3	329.6	273.3	13707.8	181733	2796.9

(d) S4 scenario (changed temperature and changed rainfall in 2050).

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	27.2	93.4	193.2	247.1	132.6	-	-	-	-	-	-	-	693.5	30896	214.3
sorghum	-	-	-	-	-	-	118.6	263.1	267.4	174.2	5.7	-	829.0	1037	8.6
Maize	-	-	-	33.7	220.0	429.0	380.7	64.7	-	-	-	-	1128.1	2212	25.0
Barley	114.8	104.7	12.6	-	-	-	-	-	-	-	24.8	94.3	351.2	652	2.3
Tomato	-	-	-	5.0	167.2	291.2	405.3	366.0	176.1	-	-	-	1410.8	4383	61.8
Potato	-	2.4	75.1	209.6	338.3	361.4	66.2	-	-	-	-	-	1053.0	3446	36.3
Other vegetables	-	-	-	5.9	206.0	346.8	368.6	20.9	-	-	-	-	948.2	40879	387.6
Clover	29.3	44.5	115.5	206.7	281.3	336.3	342.6	309.4	245.6	81.4	47.2	32.2	2072.0	50090	1037.9
Dates	85.2	104.8	142.8	187.2	285.1	348.3	354.9	320.8	264.8	210.8	120.6	86.8	2512.1	43178	1084.7
Citrus	59.8	77.3	104.6	155.4	217.6	262.2	241.6	217.1	174.8	140.8	82.3	62.0	1795.5	3582	64.3
Grapes	18.1	32.3	35.1	44.1	139.6	282.8	308.5	278.3	228.5	180.4	75.1	21.3	1644.1	1378	22.7
Total	334.4	459.4	678.9	1094.7	1987.7	2658.0	2587.0	1840.3	1357.2	787.6	355.7	296.6	14437.5	181733	2945.4

Table A.2: CWR for different crops under various scenarios in Makkah region

(a) S1 scenario (current temperature and rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	39.4	112.7	205.1	225	107.2	-	-	-	-	-	-	-	689.4	371	2.6
Millet (Grains)	40.0	137.6	178.6	67.2	-	-	-	-	-	-	-	-	423.4	1255	5.3
Sorghum	-	35.3	125.7	201.1	203.3	42.8	-	-	-	-	-	-	608.2	5853	35.6
Maize	-	-	-	40.7	166.3	274.8	250.9	46.2	-	-	-	-	778.9	619	4.8
Barley	160.6	130.9	17.4	-	-	-	-	-	-	-	20.0	121.7	450.6	306	1.4
Tomato	-	-	-	4.0	131.7	189.2	269.9	264.3	137.9	-	-	-	997.0	2041	20.3
Potato	-	2.7	89.1	191.9	259.1	235.1	43.0	-	-	-	-	-	820.9	172	1.4
Other vegetables	-	-	-	4.7	160.3	224.0	244.7	14.5	-	-	-	-	648.2	9080	58.9
Clover	46.4	54.0	125.8	188.5	214.3	217.6	228.3	224.0	192.9	62.6	39.3	39.4	1633.1	638	10.4
Date	134.5	145.8	178.0	198.0	225.0	227.8	234.4	206.7	181.6	142.3	110.2	110.9	2095.2	10771	225.7
Citrus	91.9	100.0	123.0	137.8	162.8	165.5	173.7	160.7	141.2	110.8	82.8	82.8	1533.0	1711	26.2
Grapes	31.9	39.2	85.4	158.9	193.4	196.5	206.2	198.6	129.4	46.7	25.1	25.4	1336.7	727	9.7
Total	544.7	758.2	1128.1	1417.8	1823.4	1773.3	1651.1	1115.0	783.0	362.4	277.4	380.2	12014.6	33544	402.3

(b) S2 scenario (changed temperature in 2050 and current rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	42.8	121.2	218.3	237.9	112.9	-	-	-	-	-	-	-	733.1	371	2.7
Millet (Grains)	43.7	147.7	190.0	71.2	-	-	-	-	-	-	-	-	452.6	1255	5.7
Sorghum	-	38.2	133.7	212.5	214.3	45.2	-	-	-	-	-	-	643.9	5853	37.7
Maize	-	-	-	43.1	175.4	291.5	268.4	49.7	-	-	-	-	828.1	619	5.1
Barley	173.5	140.7	18.7	-	-	-	-	-	-	-	22.7	132.2	487.8	306	1.5
Tomato	-	-	-	4.3	139.1	201.0	289.0	285.0	150.5	-	-	-	1068.9	2041	21.8
Potato	-	2.9	95.0	202.9	273.3	249.6	45.9	-	-	-	-	-	869.6	172	1.5
Other vegetables	-	-	-	5.0	169.3	237.9	262.0	15.6	-	-	-	-	689.8	9080	62.6
Clover	50.9	58.3	133.8	199.2	225.9	230.9	244.3	241.5	210.9	68.8	44.1	43.7	1752.3	638	11.2
Date	145.3	156.3	189.0	208.9	236.9	241.4	250.4	223.3	198.9	156.3	121.0	120.7	2248.4	10771	242.2
Citrus	99.4	107.3	130.6	145.4	171.3	175.3	185.6	173.6	154.7	121.6	91.1	90.2	1646.1	1711	28.2
Grapes	35.2	42.4	90.9	167.8	203.8	208.4	220.5	214.0	141.1	51.3	28.7	28.7	1432.8	727	10.4
Total	590.8	815.0	1200.0	1498.2	1922.2	1881.2	1766.1	1202.7	856.1	398.0	307.6	415.5	12853.4	33544	430.6

Table A.2: continued

(c) S3 scenario (changed rainfall in 2050 and current temperature)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	36.4	110.7	204.8	225.2	107.5	-	-	-	-	--	-	-	684.6	371	2.5
Millet (Grains)	35.0	135.6	178.2	67.2	-	-	-	-	-	-	-	-	416.0	1255	5.2
Sorghum	-	33.9	125.3	201.2	203.7	42.8	-	-	-	-	-	-	606.9	5853	35.5
Maize	-	-	-	40.8	166.7	274.8	250.7	44.9	-	-	-	-	777.9	619	4.8
Barley	154.7	128.9	17.1	-	-	-	-	-	-	-	20.3	120.1	441.1	306	1.3
Tomato	-	-	-	4.0	132.1	189.3	269.8	258.7	130.7	-	-	-	984.6	2041	20.1
Potato	-	2.7	88.7	192.0	259.5	235.2	43.0	-	-	-	-	-	821.1	172	1.4
Other vegetables	-	-	-	4.7	160.7	224.0	244.6	14.5	-	-	-	-	648.5	9080	58.9
Clover	40.5	52.0	125.4	188.6	214.7	217.6	228.2	218.4	182.5	56.8	39.2	37.8	1601.7	638	10.2
Date	128.6	143.8	177.6	198.0	225.4	227.8	234.3	201.1	171.1	136.5	110.1	109.3	2063.6	10771	222.3
Citrus	86.0	98.0	122.6	137.9	163.2	165.6	173.6	155.2	130.8	105.0	82.7	81.3	1501.9	1711	25.7
Grapes	26.0	37.2	85.0	159.0	193.8	196.5	206.1	193.0	118.9	40.9	25.0	23.8	1305.2	727	9.5
Total	507.2	742.8	1124.7	1418.6	1827.3	1773.6	1650.3	1085.8	734.0	339.2	277.3	372.3	11853.1	33544	397.5

(d) S4 scenario (changed temperature and changed rainfall in 2050).

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	39.9	119.2	217.8	238	113.4	-	-	-	-	-	-	-	728.3	371	2.7
Millet (Grains)	38.7	145.7	189.6	71.2	-	-	-	-	-	-	-	-	445.2	1255	5.6
Sorghum	-	36.7	133.3	212.6	214.7	45.3	-	-	-	-	-	-	642.6	5853	37.6
Maize	-	-	-	43.2	175.8	291.6	268.3	48.4	-	-	-	-	827.3	619	5.1
Barley	167.6	138.7	18.4	-	-	-	-	-	-	-	23.0	130.6	478.3	306	1.5
Tomato	-	-	-	4.3	139.5	201.1	288.8	279.5	143.3	-	-	-	1056.5	2041	21.6
Potato	-	2.9	94.6	203.0	273.7	249.6	45.9	-	-	-	-	-	869.7	172	1.5
Other vegetables	-	-	-	5.0	169.7	237.9	261.9	15.6	-	-	-	-	690.1	9080	62.7
Clover	45.0	56.3	133.4	199.3	226.3	230.9	244.2	236.0	200.4	63.0	43.9	42.1	1720.8	638	11.0
Date	139.3	154.3	188.6	209.0	237.3	241.4	250.3	217.7	188.4	150.5	120.8	119.1	2216.7	10771	238.8
Citrus	93.5	105.3	130.2	145.5	171.7	175.4	185.4	168.1	144.2	115.8	90.9	88.6	1614.6	1711	27.6
Grapes	29.3	40.5	90.5	167.9	204.2	208.4	220.4	208.4	130.7	45.5	28.6	27.1	1401.5	727	10.2
Total	553.3	799.6	1196.4	1499.0	1926.3	1881.6	1765.2	1173.7	807.0	374.8	307.2	407.5	12691.6	33544	425.8

Table A.3: CWR for different crops under various scenarios in Madinah region

(a) S1 scenario (current temperature and rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	29.7	100.9	223.5	263.6	129.4	-	-	-	-	-	-	-	747.1	194	1.4
Millet (Grains)	39.1	123.9	182.4	51.0	-	-	-	-	-	-	-	-	396.4	2	0.01
Maize	-	-	-	43.4	199.2	331.2	311.2	55.2	-	-	-	-	940.2	1	0.01
Barley	116.5	110.5	17.0	-	-	-	-	-	-	-	26.4	101.1	371.5	12	0.04
Tomato	-	-	-	5.0	159.5	231.2	337.4	309.3	146.5	-	-	-	1188.9	1050	12.5
Potato	-	2.5	94.5	223.3	316.2	286.6	53.1	-	-	-	-	-	976.2	2	0.02
Other vegetables	-	-	-	5.8	194.7	272.6	305.6	17.4	-	-	-	-	796.1	983	7.8
Clover	35.4	49.4	135.8	217.5	259.5	265.1	285.6	262.5	205.6	75.1	49.8	40.3	1881.6	2485	46.8
Date	89.6	113.4	183.4	222.6	265.4	271.0	292.0	267.8	213.7	170.5	123.2	95.6	2308.2	18576	428.8
Citrus	63.8	82.4	124.3	164.2	198.1	203.3	206.5	189.9	153.3	128.5	89.1	69.3	1672.7	755	12.6
Grapes	24.6	36.7	90.3	181.1	232.6	238.0	256.5	231.1	134.3	56.0	35.1	29.3	1545.6	3105	48.0
Total	398.7	619.7	1051.2	1377.5	1954.6	2099.0	2047.9	1333.2	853.4	430.1	323.6	335.6	12824.5	27165	558.0

(b) S2 scenario (changed temperature in 2050 and current rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	31.9	107.3	235.3	276.2	134.6	-	-	-	-	-	-	-	785.3	194	1.5
Millet (Grains)	42.2	131.6	192.0	53.7	-	-	-	-	-	-	-	-	419.5	2	0.01
Maize	-	-	-	45.8	206.6	343.2	325.8	58.0	-	-	-	-	979.4	1	0.01
Barley	124.7	117.5	18.0	-	-	-	-	-	-	-	28.7	108.2	397.1	12	0.05
Tomato	-	-	-	5.2	165.8	239.8	353.4	324.5	154.3	-	-	-	1243.0	1050	13.1
Potato	-	2.7	99.9	233.9	328.1	297.1	55.5	-	-	-	-	-	1017.2	2	0.02
Other vegetables	-	-	-	6.0	202.3	282.7	320.1	18.3	-	-	-	-	829.4	983	8.2
Clover	38.3	52.5	143.0	227.8	269.2	274.7	299.1	275.4	216.9	80.3	54.0	43.4	1974.6	2485	49.1
Date	96.1	120.6	192.8	232.7	274.8	280.4	305.3	280.4	224.9	182.1	132.8	102.5	2425.4	18576	450.5
Citrus	68.4	87.4	130.7	171.8	205.1	210.3	216.7	199.6	162.0	137.0	95.8	74.1	1758.9	755	13.3
Grapes	26.8	39.1	95.3	189.5	241.1	246.5	268.4	242.2	141.3	59.9	38.3	31.6	1620.0	3105	50.3
Total	428.4	658.7	1107.0	1442.6	2027.6	2174.7	2144.3	1398.4	899.4	459.3	349.6	359.8	13449.8	27165	586.0

Table A.3: continued

(c) S3 scenario (changed rainfall in 2050 and current temperature)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	27.3	102.2	226.8	265.2	129.4	-	-	-	-	-	-	-	750.9	194	1.5
Millet (Grains)	33.9	125.1	185.7	52.0	-	-	-	-	-	-	-	-	396.7	2	0.01
Maize	-	-	-	44.3	199.1	331.6	311.3	54.7	-	-	-	-	941.0	1	0.01
Barley	111.3	111.7	18.0	-	-	-	-	-	-	-	27.5	99.6	368.1	12	0.04
Tomato	-	-	-	5.0	159.4	231.6	337.6	305.8	138.1	-	-	-	1177.5	1050	12.4
Potato	-	2.5	97.8	224.9	316.1	287.0	53.2	-	-	-	-	-	981.5	2	0.02
Other vegetables	-	-	-	5.8	194.6	273.0	305.7	17.4	-	-	-	-	796.5	983	7.8
Clover	30.2	50.5	139.0	219.1	259.5	265.5	285.8	259.0	194.0	74.7	51.4	38.9	1867.6	2485	46.4
Date	84.3	114.6	186.7	224.2	265.3	271.4	292.1	264.3	202.1	170.0	124.9	94.1	2294.0	18576	426.1
Citrus	58.6	83.6	127.6	165.8	198.0	203.7	206.7	186.5	141.7	128.1	90.7	67.9	1658.9	755	12.5
Grapes	19.4	37.9	93.6	182.6	232.5	238.4	256.6	227.6	122.6	55.6	36.7	27.8	1531.3	3105	47.5
Total	365.0	628.1	1075.2	1388.9	1953.9	2102.2	2049.0	1315.3	798.5	428.4	331.2	328.3	12764.0	27165	554.3

(d) S4 scenario (changed temperature and changed rainfall in 2050).

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	29.5	108.4	238.6	277.7	134.6	-	-	-	-	-	-	-	788.8	194	1.5
Millet (Grains)	37.0	132.7	195.2	54.7	-	-	-	-	-	-	-	-	419.6	2	0.01
Maize	-	-	-	46.6	206.5	343.6	325.9	57.4	-	-	-	-	980.0	1	0.01
Barley	119.5	118.7	19.0	-	-	-	-	-	-	-	29.9	106.8	393.9	12	0.05
Tomato	-	-	-	5.2	165.7	240.2	353.5	321.0	145.9	-	-	-	1231.5	1050	12.9
Potato	-	2.7	103.1	235.5	328.0	297.5	55.5	-	-	-	-	-	1022.3	2	0.02
Other vegetables	-	-	-	6.0	202.2	283.1	320.3	18.3	-	-	-	-	829.9	983	8.2
Clover	33.1	53.7	146.3	229.3	269.1	275.1	299.3	271.9	205.3	79.8	55.7	42.0	1960.6	2485	48.7
Date	90.9	121.8	196.1	234.2	274.7	280.8	305.4	276.9	213.3	181.6	134.4	101.0	2411.1	18576	447.9
Citrus	63.1	88.6	134.0	173.3	205.0	210.7	216.8	196.1	150.3	136.6	97.5	72.7	1744.7	755	13.2
Grapes	21.6	40.3	98.5	191.1	241.0	246.9	268.6	238.8	129.7	59.5	39.9	30.1	1606.0	3105	49.9
Total	394.7	666.9	1130.8	1453.6	2026.8	2177.9	2145.3	1380.4	844.5	457.5	357.4	352.6	13388.4	27165	582.4

Table A.4: CWR for different crops under various scenarios in Qaseem region

(a) S1 scenario (current temperature and rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	20.0	76.5	141.9	210.9	127.9	-	-	-	-	-	-	-	577.2	22792	131.6
Maize	-	-	-	25.1	206.0	354.1	323.6	55.2	-	-	-	-	964.0	5983	57.7
Barley	86.3	58.3	-	-	-	-	-	-	-	-	37.0	74.7	256.3	55	0.1
Tomato	-	-	-	56.0	179.1	300.6	351.7	283.9	38.2	-	-	-	1209.5	920	11.1
Potato	-	2.1	32.7	177.0	319.6	301.3	55.9	-	-	-	-	-	888.6	3826	34.0
Other vegetables	-	-	-	5.3	194.9	287.3	314.7	17.6	-	-	-	-	819.8	6671	54.7
Clover	18.2	32.7	69.5	173.1	264.8	279.5	293.2	261.4	199.0	73.1	33.9	8.2	1706.6	14786	252.3
Dates	63.0	87.1	113.2	182.5	276.9	292.1	306.4	272.6	211.2	169.6	100.4	55.2	2130.2	39303	837.2
Citrus	50.8	70.7	70.1	121.6	198.0	223.6	235.4	210.6	155.2	140.7	81.4	42.4	1600.5	2014	32.2
Grapes	9.3	22.0	31.1	142.4	240.5	254.2	266.8	233.3	132.8	53.8	20.6	1.0	1407.8	1058	14.9
Total	247.6	349.4	458.5	1093.9	2007.7	2292.7	2147.7	1334.6	736.4	437.2	273.3	181.5	11560.5	97408	1425.9

(b) S2 scenario (changed temperature in 2050 and current rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	22.2	82.5	153.5	223.8	133.8	-	-	-	-	-	-	-	615.8	22792	140.4
Maize	-	-	-	27.6	215.0	368.4	338.0	57.7	-	-	-	-	1006.7	5983	60.2
Barley	94.6	63.2	-	-	-	-	-	-	-	-	41.5	83.4	282.7	55	0.2
Tomato	-	-	-	59.7	187.3	312.9	367.4	297.2	40.1	-	-	-	1264.6	920	11.6
Potato	-	2.3	38.0	188.1	333.7	313.7	58.3	-	-	-	-	-	934.1	3826	35.7
Other vegetables	-	-	-	5.6	203.8	299.2	328.8	18.4	-	-	-	-	855.8	6671	57.1
Clover	21.1	35.7	76.7	183.9	276.3	290.8	306.2	273.7	210.1	78.6	38.2	11.5	1802.8	14786	266.6
Dates	69.6	94.0	122.9	193.4	288.5	303.4	319.5	284.9	222.5	182.0	109.9	62.4	2253.0	39303	885.5
Citrus	50.8	70.7	70.1	121.6	198.0	223.6	235.4	210.6	155.2	140.7	81.4	42.4	1600.5	2014	32.2
Grapes	11.4	24.3	36.0	151.4	250.9	264.4	278.4	244.1	139.9	58.0	23.8	2.7	1485.3	1058	15.7
Total	269.7	372.7	497.2	1155.1	2087.3	2376.4	2232.0	1386.6	767.8	459.3	294.8	202.4	12101.3	97408	1505.2

Table A.4: Continued

(c) S3 scenario (changed rainfall in 2050 and current temperature)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	14.3	73.5	141.8	214.4	129.6	-	-	-	-	-	-	-	573.6	22792	130.7
Maize	-	-	-	27.7	207.7	354.1	323.5	54.8	-	-	-	-	967.8	5983	57.9
Barley	74.8	55.3	-	-	-	-	-	-	-	-	35.2	70.3	235.6	55	0.1
Tomato	-	-	-	57.9	180.9	300.6	351.6	282.5	37.8	-	-	-	1211.3	920	11.1
Potato	-	2.1	32.5	180.5	321.3	301.3	55.9	-	-	-	-	-	893.6	3826	34.2
Other vegetables	-	-	-	5.3	196.7	287.3	314.6	17.6	-	-	-	-	821.5	6671	54.8
Clover	6.7	29.7	69.3	176.6	266.5	279.4	293.1	260.0	196.2	73.3	32.1	4.4	1687.3	14786	249.5
Dates	51.5	84.1	113.1	186.0	278.6	292.1	306.3	271.1	208.5	169.8	98.5	50.8	2110.4	39303	829.5
Citrus	34.3	62.6	63.3	117.7	191.8	215.4	225.9	200.3	143.9	131.2	72.2	32.5	1491.1	2014	30.0
Grapes	1.9	19.0	30.9	145.9	242.3	254.2	266.7	231.9	130.0	54.0	18.8	0.0	1395.6	1058	14.8
Total	183.5	326.3	450.9	1112.0	2015.4	2284.4	2137.6	1318.2	716.4	428.3	256.8	158.0	11387.8	97408	1412.6

(d) S4 scenario (changed temperature and changed rainfall in 2050)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	16.6	79.5	153.3	227.3	135.6	-	-	-	-	-	-	-	612.3	22792	139.6
Maize	-	-	-	30.2	216.7	368.4	337.8	57.4	-	-	-	-	1010.5	5983	60.5
Barley	83.0	60.1	-	-	-	-	-	-	-	-	39.7	79.0	261.8	55	0.1
Tomato	-	-	-	61.6	189.0	312.9	367.3	295.8	39.7	-	-	-	1266.3	920	11.6
Potato	-	2.3	37.8	191.6	335.4	313.7	58.3	-	-	-	-	-	939.1	3826	35.9
Other vegetables	-	-	-	5.6	205.6	299.2	328.7	18.4	-	-	-	-	857.5	6671	57.2
Clover	9.6	32.7	76.5	187.4	278.1	290.8	306.1	272.3	207.3	78.8	36.3	7.0	1782.9	14786	263.6
Dates	58.0	90.9	122.7	196.9	290.2	303.4	319.4	283.4	219.8	182.2	108.1	58.0	2233.0	39303	877.6
Citrus	39.3	67.7	69.9	125.2	199.7	223.5	235.3	209.2	152.4	140.8	79.6	38.0	1580.6	2014	31.8
Grapes	2.7	21.3	35.8	154.9	252.6	264.4	278.3	242.7	137.1	58.1	22.0	0.6	1470.5	1058	15.6
Total	209.2	354.5	496.0	1180.7	2102.9	2376.3	2231.2	1379.2	756.3	459.9	285.7	182.6	12014.5	97408	1493.6

Table A.5: CWR for different crops under various scenarios in Eastern region

(a) S1 scenario (current temperature and rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	9.7	46.0	118.0	170.2	96.3	-	-	-	-	-	-	-	440.2	30691	135.1
Maize	-	-	-	26.7	160.9	318.5	287.7	50.2	-	-	-	-	844.1	282	2.4
Barley	56.1	41.7	-	-	-	-	-	-	-	-	20.4	63.1	181.3	226	0.4
Tomato	-	-	-	3.6	124.4	220.0	308.5	281.5	133.2	-	-	-	1071.2	1605	17.2
Potato	-	1.8	33.9	145.7	249.5	270.5	49.7	-	-	-	-	-	751.0	135	1.0
Other vegetables	-	-	-	4.2	153.5	260.6	280.7	16.0	-	-	-	-	714.9	4926	35.2
Clover	8.5	10.9	61.4	141.4	204.8	250.1	259.0	236.7	185.3	58.9	21.5	13.5	1451.9	2673	38.8
Dates	38.7	53.8	83.5	142.9	211.0	260.6	270.9	247.8	200.5	152.4	74.0	52.7	1788.9	13548	242.4
Citrus	20.4	32.6	54.7	100.0	150.4	190.3	200.7	182.0	144.8	107.2	51.1	32.0	1266.2	820	10.4
Grapes	4.0	3.3	8.6	64.5	170.4	225.0	233.3	213.2	170.2	92.8	13.8	8.6	1207.8	177	2.1
Total	137.5	190.2	360.1	799.1	1521.1	1995.7	1890.5	1227.5	834.0	411.2	180.7	170.0	9717.5	55083	485.0

(b) S2 scenario (changed temperature in 2050 and current rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	11.5	51.4	127.7	179.8	101.2	-	-	-	-	-	-	-	471.6	30691	144.7
Maize	-	-	-	28.5	168.9	333.3	303.5	53.1	-	-	-	-	887.3	282	2.5
Barley	62.8	46.9	-	-	-	-	-	-	-	-	22.5	70.1	202.4	226	0.5
Tomato	-	-	-	3.8	130.8	230.4	325.5	298.1	142.0	-	-	-	1130.6	1605	18.1
Potato	-	1.9	38.3	154.0	261.6	283.2	52.3	-	-	-	-	-	791.3	135	1.1
Other vegetables	-	-	-	4.4	161.3	272.9	296.2	16.9	-	-	-	-	751.7	4926	37.0
Clover	9.8	13.7	67.4	149.5	214.7	261.7	273.3	250.7	197.8	64.2	25.0	16.1	1544.0	2673	41.3
Dates	44.0	59.7	90.9	150.8	220.8	272.4	285.8	262.3	214.0	165.1	82.4	58.8	1907.0	13548	258.4
Citrus	24.1	36.9	60.2	105.7	157.4	198.8	211.6	192.6	154.4	116.0	57.2	36.4	1351.4	820	11.1
Grapes	5.0	4.7	10.3	68.6	178.6	235.3	245.9	225.6	181.5	100.4	15.8	9.8	1281.6	177	2.3
Total	157.3	215.3	394.9	845.1	1595.3	2088.1	1994.2	1299.3	889.7	445.6	202.9	191.2	10318.9	55083	516.9

Table A.5: Continued

(c) S3 scenario (changed rainfall in 2050 and current temperature)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	4.8	41.1	117.6	174.6	97.6	-	-	-	-	-	-	-	435.7	30691	133.7
Maize	-	-	-	29.9	162.3	318.6	287.7	50.0	-	-	-	-	848.4	282	2.4
Barley	44.2	36.7	-	-	-	-	-	-	-	-	19.3	58.6	158.9	226	0.4
Tomato	-	-	-	3.6	125.8	220.0	308.4	280.4	131.6	-	-	-	1069.8	1605	17.2
Potato	-	1.8	33.5	150.1	250.9	270.6	49.7	-	-	-	-	-	756.5	135	1.0
Other vegetables	-	-	-	4.2	154.9	260.6	280.6	16.0	-	-	-	-	716.3	4926	35.3
Clover	1.4	6.8	61.0	145.8	206.2	250.1	259.0	235.6	183.0	58.9	20.3	10.2	1438.3	2673	38.4
Dates	26.8	48.8	83.1	147.3	212.4	260.6	270.9	246.6	198.3	152.4	72.3	48.2	1767.9	13548	239.5
Citrus	10.1	27.7	54.3	104.4	151.8	190.3	200.6	180.9	142.6	107.2	49.4	27.6	1246.9	820	10.2
Grapes	0.0	1.1	8.9	68.9	171.8	225.0	233.2	212.1	168.0	92.7	12.6	5.6	1200.0	177	2.1
Total	87.4	164.0	358.5	828.6	1533.6	1995.9	1890.0	1221.6	823.5	411.1	174.0	150.3	9638.6	55083	480.2

(d) S4 scenario (changed temperature and changed rainfall in 2050).

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	6.1	46.5	127.3	184.2	102.5	-	-	-	-	-	-	-	466.5	30691	143.2
Maize	-	-	-	31.7	170.3	333.4	303.4	52.9	-	-	-	-	891.7	282	2.5
Barley	51.0	42.0	-	-	-	-	-	-	-	-	21.4	65.7	180.0	226	0.4
Tomato	-	-	-	3.8	132.2	230.5	325.5	297.0	140.4	-	-	-	1129.3	1605	18.1
Potato	-	1.9	38.0	158.4	263.0	283.2	52.3	-	-	-	-	-	796.8	135	1.1
Other vegetables	-	-	-	4.4	162.7	272.9	296.2	16.9	-	-	-	-	753.1	4926	37.1
Clover	2.3	8.7	67.0	153.9	216.1	261.8	273.2	249.6	195.5	64.2	23.3	12.1	1527.8	2673	40.8
Dates	32.1	54.8	90.6	155.2	222.2	272.5	285.7	261.1	211.8	165.0	80.7	54.3	1885.9	13548	255.5
Citrus	13.2	32.0	59.9	110.1	158.8	198.9	211.5	191.5	152.2	115.9	55.5	31.9	1331.4	820	10.9
Grapes	0.0	2.0	10.6	73.0	180.0	235.3	245.9	224.5	179.3	100.3	14.6	6.7	1272.3	177	2.3
Total	104.6	187.8	393.4	874.7	1607.8	2088.5	1993.7	1293.5	879.3	445.4	195.6	170.7	10234.8	55083	511.9

Table A.6: CWR for different crops under various scenarios in Aseer region

(a) S1 scenario (current temperature and rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	29.6	81.4	113.2	142.8	60.0	-	-	-	-	-	-	-	427.0	3155	13.5
Millet (Grains)	106.4	64.0	-	-	-	-	-	-	-	-	12.1	74.0	256.5	78	0.2
Sorghum	-	-	-	1.7	30.0	151.3	169.1	113.6	3.5	-	-	-	469.2	2173	10.2
Maize	-	-	-	4.1	104.0	220.7	177.4	24.9	-	-	-	-	531.1	201	1.1
Barley	121.4	65.0	-	-	-	-	-	-	-	-	39.0	110.6	336.0	660	2.2
Tomato	-	-	-	-	7.2	104.7	136.5	174.5	208.8	100.4	-	-	732.1	1547	11.3
Potato	-	2.2	15.9	114.6	182.9	189.3	28.6	-	-	-	-	-	533.5	67	0.4
Other Vegetables	-	-	-	3.9	99.3	179.3	172.8	11.0	-	-	-	-	466.3	1142	5.3
Clover	35.7	35.0	46.8	111.4	144.8	174.4	159.8	142.6	170.9	58.3	35.2	35.1	1150.0	1419	16.3
Date	102.8	107.4	90.6	119.9	154.4	183.6	165.6	128.8	161.4	135.0	92.5	87.8	1529.8	5075	77.6
Citrus	70.5	71.4	44.6	69.3	103.1	132.4	117.1	93.8	124.2	104.9	70.7	67.6	1069.6	329	3.5
Grapes	24.8	23.5	0.0	32.3	115.2	156.3	141.3	125.5	155.3	94.9	23.7	24.8	917.6	434	4.0
Total	491.2	449.9	311.1	600.0	1000.9	1492.0	1268.2	814.7	824.1	493.5	273.2	399.9	8418.7	16280	145.6

(b) S2 scenario (changed temperature in 2050 and current rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	32.2	88.2	124.9	154.2	65.1	-	-	-	-	-	-	-	464.6	3155	14.7
Millet (Grains)	115.5	69.5	-	-	-	-	-	-	-	-	13.5	80.1	278.6	78	0.2
Sorghum	-	-	-	1.8	33.2	152.7	177.8	122.1	3.7	-	-	-	491.3	2173	10.7
Maize	-	-	-	6.3	109.0	220.3	184.4	26.9	-	-	-	-	546.9	201	1.1
Barley	131.7	70.7	-	-	-	-	-	-	-	-	43.1	119.5	365.0	660	2.4
Tomato	-	-	-	-	7.5	106.3	144.8	187.7	224.6	108.8	-	-	779.7	1547	12.1
Potato	-	2.3	21.1	124.1	193.5	190.7	29.3	-	-	-	-	-	561.0	67	0.4
Other Vegetables	-	-	-	4.2	106.1	180.9	181.8	11.7	-	-	-	-	484.7	1142	5.5
Clover	39.3	38.5	53.6	120.3	153.1	176.1	168.2	153.0	183.5	63.5	39.0	38.3	1226.4	1419	17.4
Date	111.0	115.4	99.8	129.1	162.9	184.9	172.8	139.3	174.1	146.8	101.0	95.1	1632.2	5075	82.8
Citrus	76.5	77.3	51.4	75.9	107.7	132.0	121.8	102.0	134.0	114.0	77.2	73.0	1142.8	329	3.8
Grapes	27.5	26.1	0.0	36.8	121.5	157.1	148.2	134.2	165.8	102.4	26.6	27.2	973.4	434	4.2
Total	533.7	488.0	350.8	652.7	1059.6	1501.0	1329.1	876.9	885.7	535.5	300.4	433.2	8946.6	16280	155.3

Table A.6: Continued

(c) S3 scenario (changed rainfall in 2050 and current temperature)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	27.0	76.2	118.4	142.2	60.8	-	-	-	-	-	-	-	424.6	3155	13.4
Millet (Grains)	101.4	58.8	-	-	-	-	-	-	-	-	12.5	68.7	241.4	78	0.2
Sorghum	-	-	-	1.7	31.0	152.2	171.2	105.4	3.5	-	-	-	465.0	2173	10.1
Maize	-	-	-	3.7	105.0	221.6	179.5	23.3	-	-	-	-	533.1	201	1.1
Barley	116.4	59.8	-	-	-	-	-	-	-	-	38.3	105.3	319.8	660	2.1
Tomato	-	-	-	-	7.2	105.6	138.6	166.3	190.4	86.8	-	-	694.9	1547	10.8
Potato	-	2.2	21.0	114.0	184.0	190.2	29.5	-	-	-	-	-	540.9	67	0.4
Other Vegetables	-	-	-	3.9	100.3	180.2	175.0	11.0	-	-	-	-	470.4	1142	5.4
Clover	30.7	29.9	52.0	110.8	145.9	175.3	162.0	134.4	152.4	40.0	34.5	29.8	1097.7	1419	15.6
Date	97.7	102.2	95.8	119.4	155.5	184.5	167.8	120.6	142.9	116.7	91.9	82.6	1477.6	5075	75.0
Citrus	65.5	66.3	49.8	68.7	104.1	133.3	119.2	85.7	105.7	86.5	70.0	62.3	1017.1	329	3.3
Grapes	19.7	18.3	0.0	31.7	116.2	157.1	143.4	117.3	136.8	76.6	23.0	19.6	859.7	434	3.7
Total	458.4	413.7	337.0	596.1	1010.0	1500.0	1286.2	764.0	731.7	406.6	270.2	368.3	8142.2	16280	141.0

(d) S4 scenario (changed temperature and changed rainfall in 2050).

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	29.8	83.1	130.1	153.8	65.9	-	-	-	-	-	-	-	462.7	3155	14.6
Millet (Grains)	110.4	64.4	-	-	-	-	-	-	-	-	13.9	74.8	263.5	78	0.2
Sorghum	-	-	-	1.8	34.2	153.5	179.9	113.9	3.7	-	-	-	487.0	2173	10.6
Maize	-	-	-	5.5	110.0	221.2	186.5	25.3	-	-	-	-	548.5	201	1.1
Barley	126.6	65.5	-	-	-	-	-	-	-	-	42.4	114.2	348.7	660	2.3
Tomato	-	-	-	-	7.5	107.2	146.9	179.5	206.1	95.2	-	-	742.4	1547	11.5
Potato	-	2.3	26.3	123.5	194.5	191.6	30.2	-	-	-	-	-	568.4	67	0.4
Other Vegetables	-	-	-	4.2	107.1	181.8	183.9	11.7	-	-	-	-	488.7	1142	5.6
Clover	34.2	33.3	58.8	119.7	154.2	176.9	170.4	144.8	165.0	45.2	38.3	33.0	1173.8	1419	16.7
Date	105.9	110.2	104.9	128.5	163.9	185.8	174.9	131.1	155.6	128.5	100.3	89.8	1579.4	5075	80.2
Citrus	71.5	72.1	56.6	75.3	108.7	132.9	123.9	93.8	115.6	95.6	76.5	67.8	1090.3	329	3.6
Grapes	22.4	20.9	0.0	36.2	122.5	158.0	150.4	126.1	147.3	84.1	25.9	22.0	915.8	434	4.0
Total	500.8	451.8	376.7	648.5	1068.5	1508.9	1347.0	826.2	793.3	448.6	297.3	401.6	8669.2	16280	150.6

Table A.7: CWR for different crops under various scenarios in Tabouk region

(a) S1 scenario (current temperature and rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	22.1	81	185	254.3	112.4	-	-	-	-	-	-	-	654.8	17889	117.1
Maize	-	-	-	45.4	174.1	303.4	286.7	50.3	-	-	-	-	859.9	20	0.2
Barley	92.1	90.1	13.3	-	-	-	-	-	-	-	12.7	69.4	277.6	278	0.8
Tomato	-	-	-	70.6	152.8	258.4	312.4	262.4	37.6	-	-	-	1094.2	389	4.3
Potato	-	2.1	76.6	214.2	272.7	258.6	49.0	-	-	-	-	-	873.2	2342	20.5
Other vegetables	-	-	-	5.2	166.6	247.0	279.6	16.0	-	-	-	-	714.4	1082	7.7
Clover	23.5	38.1	112.4	211.2	226.3	240.6	261.2	242.4	199.8	60.8	27.5	24.3	1668.1	9008	150.3
Date	67.5	90.5	154.4	220.8	236.6	251.5	273.0	253.1	212.9	145.5	80.1	63.4	2049.3	2249	46.1
Citrus	51.1	71.0	108.8	154.1	164.9	177.1	198.6	184.4	157.1	111.6	59.0	48.1	1485.8	1868	27.8
Grapes	14.7	27.8	74.9	178.5	204.5	217.9	236.6	215.4	133.6	43.8	17.0	16.4	1381.1	1154	15.9
Total	271.0	400.6	725.4	1354.3	1710.9	1954.5	1897.1	1224.0	741.0	361.7	196.3	221.6	11058.4	36279	390.6

(b) S2 scenario (changed temperature in 2050 and current rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	24.4	87.3	194.8	268.4	118.4	-	-	-	-	-	-	-	693.3	17889	124.0
Maize	-	-	-	48.1	182.9	317.3	300.9	53.0	-	-	-	-	902.2	20	0.2
Barley	100.9	97.3	14.1	-	-	-	-	-	-	-	14.7	76.1	303.1	278	0.8
Tomato	-	-	-	74.6	160.9	270.4	328.2	276.9	39.9	-	-	-	1150.9	389	4.5
Potato	-	2.2	81.0	226.2	286.6	270.6	51.4	-	-	-	-	-	918.0	2342	21.5
Other vegetables	-	-	-	5.5	175.5	258.6	293.7	16.8	-	-	-	-	750.1	1082	8.1
Clover	26.6	41.3	118.5	223.0	237.8	251.7	274.4	255.9	212.7	66.1	31.1	27.1	1766.2	9008	159.1
Date	74.4	97.9	162.3	232.7	248.1	262.5	286.1	266.6	226.2	157.4	88.2	69.7	2172.1	2249	48.9
Citrus	56.4	76.6	114.4	162.3	172.9	184.8	207.9	194.0	166.8	120.9	65.4	53.0	1575.4	1868	29.4
Grapes	17.0	30.2	79.0	188.3	214.7	227.7	248.2	227.1	142.0	47.8	19.7	18.6	1460.3	1154	16.9
Total	299.7	432.8	764.1	1429.1	1797.8	2043.6	1990.8	1290.3	787.6	392.2	219.1	244.5	11691.6	36279	413.4

Table A.7: Continued

(c) S3 scenario (changed rainfall in 2050 and current temperature)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	14.8	69.6	182.9	257.1	115.2	-	-	-	-	-	-	-	639.6	17889	114.4
Maize	-	-	-	47.2	177.3	303.5	286.6	50.2	-	-	-	-	864.8	20	0.2
Barley	78.3	78.8	11.7	-	-	-	-	-	-	-	10.9	64.6	244.3	278	0.7
Tomato	-	-	-	72.0	156.1	258.4	312.3	262.0	37.6	-	-	-	1098.4	389	4.3
Potato	-	2.1	74.5	217.1	275.9	258.7	49.0	-	-	-	-	-	877.3	2342	20.5
Other vegetables	-	-	-	5.2	169.9	247.1	279.5	16.0	-	-	-	-	717.7	1082	7.8
Clover	9.7	26.7	110.3	214.1	229.5	240.7	261.2	242.1	199.4	60.9	25.2	19.5	1639.3	9008	147.7
Date	53.7	79.2	152.3	223.8	239.8	251.5	272.9	252.7	212.5	145.6	77.8	58.6	2020.4	2249	45.4
Citrus	37.3	59.7	106.7	157.0	168.1	177.2	198.5	184.1	156.6	111.7	56.8	43.3	1457.0	1868	27.2
Grapes	2.3	16.4	72.7	181.5	207.7	218.0	236.5	215.0	133.2	44.0	14.7	11.7	1353.7	1154	15.6
Total	196.1	332.5	711.1	1375.0	1739.5	1955.1	1896.5	1222.1	739.3	362.2	185.4	197.7	10912.5	36279	383.8

(d) S4 scenario (changed temperature and changed rainfall in 2050).

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	17.1	76.1	192.6	271.4	121.1	-	-	-	-	-	-	-	678.3	17889	121.3
Maize	-	-	-	49.8	186.1	317.3	300.9	52.9	-	-	-	-	907.0	20	0.2
Barley	87.1	86.0	12.5	-	-	-	-	-	-	-	12.9	71.3	269.8	278	0.8
Tomato	-	-	-	76.0	164.1	270.5	328.1	276.5	39.9	-	-	-	1155.1	389	4.5
Potato	-	2.2	78.9	229.1	289.9	270.6	51.4	-	-	-	-	-	922.1	2342	21.6
Other vegetables	-	-	-	5.5	178.7	258.6	293.7	16.8	-	-	-	-	753.3	1082	8.2
Clover	12.8	30.0	116.3	225.9	241.0	251.8	274.3	255.5	212.3	66.2	28.8	22.3	1737.2	9008	156.5
Date	60.6	86.5	160.2	235.6	251.4	262.6	286.1	266.2	225.8	157.5	85.9	65.0	2143.4	2249	48.2
Citrus	42.6	65.2	112.2	165.3	176.2	184.9	207.9	193.7	166.4	121.0	63.1	48.2	1546.7	1868	28.9
Grapes	3.9	18.9	76.8	191.2	218.0	227.8	248.2	226.8	141.5	47.9	17.4	13.8	1432.2	1154	16.5
Total	224.1	364.9	749.5	1449.8	1826.5	2044.1	1990.6	1288.4	785.9	392.6	208.1	220.6	11545.1	36279	406.6

Table A.8: CWR for different crops under various scenarios in Hail region

(a) S1 scenario (current temperature and rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	1.7	57.1	166.9	202.0	105.0	-	-	-	-	-	-	-	532.7	23558	125.5
Maize	-	-	-	43.1	224.6	324.7	245.3	9.5	-	-	-	-	847.2	16967	143.7
Barley	70.9	93.4	20.6	-	-	-	-	-	-	-	-	56.1	241.0	360	0.9
Tomato	-	-	-	4.1	130.8	222.6	322.7	289.5	146.2	-	-	-	1115.9	611	6.8
Potato	-	2.1	62.2	167.6	269.8	275.6	51.8	-	-	-	-	-	829.1	5800	48.1
Other vegetables	-	-	-	4.8	162.2	263.8	292.7	16.3	-	-	-	-	739.8	3885	28.7
Clover	6.9	29.5	96.5	164.5	222.4	256.2	272.7	245.3	204.7	59.0	4.1	19.0	1580.8	7127	112.7
Dates	47.7	82.1	137.4	172.4	232.1	267.0	284.1	255.3	218.3	145.3	57.4	59.9	1959.0	18743	367.2
Citrus	32.8	62.5	93.1	113.6	160.0	196.0	208.6	187.7	150.3	110.8	35.0	44.4	1394.8	1350	18.8
Grapes	1.7	19.1	27.6	71.3	184.8	231.6	246.4	221.7	188.1	102.1	0.0	10.8	1305.2	1139	14.9
Total	161.7	345.8	604.3	943.4	1691.7	2037.5	1924.3	1225.3	907.6	417.2	96.5	190.2	10545.5	79540	867.3

(b) S2 scenario (changed temperature in 2050 and current rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	2.4	61.9	178.6	214.6	110.5	-	-	-	-	-	-	-	568.0	23558	133.8
Maize	-	-	-	46.9	235.2	338.7	257.1	10.0	-	-	-	-	887.9	16967	150.6
Barley	78.7	100.6	22.5	-	-	-	-	-	-	-	-	62.0	263.8	360	0.9
Tomato	-	-	-	4.3	137.6	232.4	338.3	305.0	156.9	-	-	-	1174.5	611	7.2
Potato	-	2.2	67.5	178.3	282.7	287.6	54.2	-	-	-	-	-	872.5	5800	50.6
Other vegetables	-	-	-	5.1	170.4	275.4	306.9	17.2	-	-	-	-	775.0	3885	30.1
Clover	9.6	32.4	103.7	175.0	232.9	267.4	285.9	258.3	220.1	64.5	6.4	21.8	1678.0	7127	119.6
Dates	53.7	88.7	147.0	182.9	242.7	278.0	297.2	268.4	234.0	157.5	66.0	66.2	2082.3	18743	390.3
Citrus	37.4	67.4	99.9	121.0	167.4	203.9	218.1	197.2	161.9	120.3	41.7	49.2	1485.4	1350	20.1
Grapes	2.5	21.3	30.6	76.6	193.4	241.3	258.0	233.3	202.0	110.4	0.9	12.9	1383.2	1139	15.8
Total	184.3	374.5	649.8	1004.7	1772.8	2124.7	2015.7	1289.4	974.9	452.7	115.0	212.1	11170.6	79540	919.0

Table A.8: Continued

(c) S3 scenario (changed rainfall in 2050 and current temperature)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	0.6	65.7	173.1	203.6	104.8	-	-	-	-	-	-	-	547.8	23558	129.1
Maize	-	-	-	44.8	224.3	324.8	245.2	9.3	-	-	-	-	848.4	16967	143.9
Barley	64.6	101.9	24.1	-	-	-	-	-	-	-	-	54.8	245.4	360	0.9
Tomato	-	-	-	4.1	130.5	222.6	322.6	286.9	142.0	-	-	-	1108.7	611	6.8
Potato	-	2.1	68.5	169.3	269.4	275.6	51.8	-	-	-	-	-	836.7	5800	48.5
Other vegetables	-	-	-	4.8	161.9	263.8	292.6	16.3	-	-	-	-	739.4	3885	28.7
Clover	3.7	38.0	102.7	166.3	222.0	256.4	272.7	242.6	197.9	57.6	4.6	17.7	1582.2	7127	112.8
Dates	41.3	90.7	143.7	174.1	231.8	267.0	284.0	252.7	211.3	143.8	59.0	58.6	1958.0	18743	367.0
Citrus	26.5	71.0	99.3	115.3	159.6	196.0	208.5	185.1	143.3	109.3	36.7	43.0	1393.6	1350	18.8
Grapes	0.6	27.6	33.9	73.0	184.4	231.6	246.3	219.1	181.1	100.7	0.2	9.5	1308.0	1139	14.9
Total	137.3	397.0	645.3	955.3	1688.7	2037.8	1923.7	1212.0	875.6	411.4	100.5	183.6	10568.2	79540	871.4

(d) S4 scenario (changed temperature and changed rainfall in 2050).

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	1.3	70.4	184.9	216.3	110.2	-	-	-	-	-	-	-	583.1	23558	137.4
Maize	-	-	-	48.6	234.9	338.7	257.0	9.8	-	-	-	-	889.0	16967	150.8
Barley	72.4	109.2	26.0	-	-	-	-	-	-	-	-	60.6	268.2	360	1.0
Tomato	-	-	-	4.3	137.2	232.4	338.1	302.4	152.7	-	-	-	1167.1	611	7.1
Potato	-	2.2	73.7	180.0	282.3	287.6	54.2	-	-	-	-	-	880.0	5800	51.0
Other vegetables	-	-	-	5.1	170.1	275.4	306.8	17.2	-	-	-	-	774.6	3885	30.1
Clover	5.4	40.9	110.0	176.7	232.6	267.4	285.8	255.7	213.2	63.0	7.2	20.4	1678.3	7127	119.6
Dates	47.4	97.2	153.3	184.6	242.3	278.0	297.1	265.8	227.1	156.0	67.7	64.8	2081.3	18743	390.1
Citrus	31.1	75.9	106.1	122.7	167.0	203.9	217.9	194.6	154.9	118.8	43.3	47.9	1484.1	1350	20.0
Grapes	1.3	29.8	36.9	78.3	193.1	241.3	257.9	230.7	195.0	108.9	1.3	11.6	1386.1	1139	15.8
Total	158.9	425.6	690.9	1016.6	1769.7	2124.7	2014.8	1276.2	942.9	446.7	119.5	205.3	11191.8	79540	923.0

Table A.9: CWR for different crops under various scenarios in Jazan region

(a) S1 scenario (current temperature and rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Millet	21.5	97.0	176.7	109.9	-	-	-	-	-	-	-	-	405.1	2422	9.8
Sorghum	-	-	-	23.1	112.3	210.9	212.0	70.0	-	-	-	-	628.3	83618	525.4
Maize	108.6	3.3	-	-	-	-	-	-	-	60.3	139.4	152.6	464.2	935	4.3
Barley	150.9	128.9	31.6	-	-	-	-	-	-	-	19.0	100.8	431.2	16	0.1
Tomato	-	-	-	3.9	123.4	180.1	253.6	234.8	133.1	-	-	-	928.9	1221	11.3
Other vegetables	-	-	-	4.6	150.5	212.5	228.5	13.9	-	-	-	-	610.0	2486	15.2
Date	117.8	116.8	159.9	166.1	198.1	204.2	210.7	193.6	194.9	169.0	129.7	109.6	1970.4	288	5.7
Citrus	84.0	82.5	110.6	107.3	133.5	150.9	155.1	139.1	141.0	123.7	97.3	77.7	1402.7	182	2.6
Total	482.8	428.5	478.8	414.9	717.8	958.6	1059.9	651.4	469.0	353.0	385.4	440.7	6840.8	91168	574.3

(b) S2 scenario (changed temperature in 2050 and current rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Millet	23.1	103.4	187.6	117.4	-	-	-	-	-	-	-	-	431.5	2422	10.5
Sorghum	-	-	-	25.0	118.8	225.0	228.0	76.3	-	-	-	-	673.1	83618	562.8
Maize	116.7	3.5	-	-	-	-	-	-	-	66.1	152.6	165.9	504.8	935	4.7
Barley	162.0	137.4	33.8	-	-	-	-	-	-	-	21.2	110.0	464.4	16	0.1
Tomato	-	-	-	4.2	130.5	192.4	272.9	254.7	144.1	-	-	-	998.8	1221	12.2
Other vegetables	-	-	-	4.9	159.2	226.9	245.9	14.9	-	-	-	-	651.8	2486	16.2
Date	126.8	124.7	170.0	176.6	208.8	217.5	226.3	209.8	210.7	183.8	142.3	119.7	2117.0	288	6.1
Citrus	90.2	87.9	117.4	114.3	140.8	160.7	166.7	151.0	153.2	135.2	106.9	85.0	1509.3	182	2.7
Total	518.8	456.9	508.8	442.4	758.1	1022.5	1139.8	706.7	508.0	385.1	423.0	480.6	7350.7	91168	615.3

Table A.9: Continued

(c) S3 scenario (changed rainfall in 2050 and current temperature)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Millet	22.8	99.9	182.4	111.2	-	-	-	-	-	-	-	-	416.3	2422	10.1
Sorghum	-	-	-	23.4	112.9	212.1	218.0	60.0	-	-	-	-	626.4	83618	523.8
Maize	112.6	3.3	-	-	-	-	-	-	-	8.2	113.3	146.1	383.5	935	3.6
Barley	154.9	131.8	34.5	-	-	-	-	-	-	-	9.1	94.3	424.6	16	0.1
Tomato	-	-	-	3.9	123.9	181.2	259.6	213.8	93.1	-	-	-	875.5	1221	10.7
Other vegetables	-	-	-	4.6	151.0	213.7	234.4	13.9	-	-	-	-	617.6	2486	15.4
Date	121.8	119.7	165.6	167.3	198.7	205.4	216.6	172.6	132.8	105.5	103.5	103.1	1812.6	288	5.2
Citrus	88.0	85.4	116.3	108.5	134.1	152.0	161.1	118.1	79.0	60.2	71.1	71.1	1244.9	182	2.3
Total	500.1	440.1	498.8	418.9	720.6	964.4	1089.7	578.4	304.9	173.9	297.0	414.6	6401.4	91168	571.0

(d) S4 scenario (changed temperature and changed rainfall in 2050).

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Millet	24.5	106.3	193.3	118.7	-	-	-	-	-	-	-	-	442.8	2422	10.7
Sorghum	-	-	-	25.3	119.3	226.1	234.0	66.3	-	-	-	-	671.0	83618	561.1
Maize	120.7	3.5	-	-	-	-	-	-	-	10.7	126.5	159.4	420.8	935	3.9
Barley	166.0	140.3	36.7	-	-	-	-	-	-	-	11.3	103.5	457.8	16	0.1
Tomato	-	-	-	4.2	131.1	193.5	278.8	233.6	104.1	-	-	-	945.3	1221	11.5
Other vegetables	-	-	-	4.9	159.7	228.1	251.8	14.9	-	-	-	-	659.4	2486	16.4
Date	130.7	127.5	175.7	177.8	209.4	218.6	232.2	188.8	148.7	120.3	116.2	113.2	1959.1	288	5.6
Citrus	94.2	90.8	123.1	115.6	141.3	161.8	172.6	130.0	91.2	71.7	80.8	78.5	1351.6	182	2.5
Total	536.1	468.4	528.8	446.5	760.8	1028.1	1169.4	633.6	344.0	202.7	334.8	454.6	6907.8	91168	611.8

Table A.10: CWR for different crops under various scenarios in Najran region

(a) S1 scenario (current temperature and rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	40.2	101.2	167.3	197.8	114.5	-	-	-	-	-	-	-	621.0	763	4.7
Barley	158.1	80.9	-	-	-	-	-	-	-	-	66.6	135.8	441.4	33	0.1
Tomato	-	-	-	4.2	142.9	215.6	277.6	263.4	164.7	-	-	-	1068.4	540	5.8
Potato	-	2.7	39.0	164.1	284.2	269.4	46.2	-	-	-	-	-	805.6	32	0.3
Other vegetables	-	-	-	4.9	174.9	256.6	253.0	14.4	-	-	-	-	703.8	927	6.5
Clover	51.3	44.5	79.8	160.7	234.6	248.4	235.0	223.4	230.3	63.4	61.1	42.3	1674.8	1914	32.1
Dates	119.4	116.0	130.3	167.0	242.2	256.4	242.5	232.2	246.3	142.8	137.6	106.1	2138.8	3367	72.0
Citrus	93.4	87.9	76.8	116.6	180.2	191.8	168.5	160.0	169.0	111.8	108.2	81.7	1545.9	1833	28.3
Grapes	37.7	30.4	1.3	65.5	197.4	225.5	213.3	202.8	210.3	100.8	45.8	29.5	1360.3	41	0.6
Total	500.1	463.6	494.5	880.8	1570.9	1663.7	1436.1	1096.2	1020.6	418.8	419.3	395.4	10360.0	9450	150.4

(b) S2 scenario (changed temperature in 2050 and current rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	43.1	108.4	179.9	208.6	119.2	-	-	-	-	-	-	-	659.2	763	5.0
Barley	168.7	86.8	-	-	-	-	-	-	-	-	71.2	145.2	471.9	33	0.2
Tomato	-	-	-	4.4	148.8	223.6	288.4	276.3	173.6	-	-	-	1115.1	540	6.0
Potato	-	2.9	44.7	173.3	295.3	279.4	47.9	-	-	-	-	-	843.5	32	0.3
Other vegetables	-	-	-	5.1	182.0	266.1	262.9	15.0	-	-	-	-	731.1	927	6.8
Clover	55.0	48.2	87.5	169.7	243.6	257.4	244.1	234.3	242.9	67.6	65.3	45.7	1761.3	1914	33.7
Dates	127.7	124.2	140.5	175.8	251.1	265.2	251.5	243.1	259.2	152.1	147.1	113.7	2251.2	3367	75.8
Citrus	99.4	93.8	84.0	123.2	186.9	198.4	175.4	168.2	178.5	118.8	115.2	87.3	1629.1	1833	29.9
Grapes	40.5	33.1	3.5	70.0	204.8	233.5	221.4	212.6	221.6	106.9	48.9	32.1	1428.9	41	0.6
Total	534.4	497.4	540.1	930.1	1631.7	1723.6	1491.6	1149.5	1075.8	445.4	447.7	424.0	10891.3	9450	158.2

Table A.10: Continued

(c) S3 scenario (changed rainfall in 2050 and current temperature)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	32.5	88.7	172.4	197.2	115.9	-	-	-	-	-	-	-	606.7	763	4.6
Barley	143.6	68.4	-	-	-	-	-	-	-	-	66.7	132.2	410.9	33	0.1
Tomato	-	-	-	4.2	144.4	215.6	277.6	258.6	158.7	-	-	-	1059.1	540	5.7
Potato	-	2.7	44.2	163.6	285.6	269.4	46.2	-	-	-	-	-	811.7	32	0.3
Other vegetables	-	-	-	4.9	176.4	256.6	253.0	14.4	-	-	-	-	705.3	927	6.5
Clover	36.9	32.0	85.0	160.2	236.0	248.4	235.0	218.5	221.5	57.7	61.1	38.6	1630.9	1914	31.2
Dates	104.9	103.5	135.5	166.4	243.7	256.4	242.5	227.4	237.5	137.1	137.7	102.4	2095.0	3367	70.5
Citrus	78.9	75.4	82.0	116.0	181.7	191.8	168.4	155.2	160.2	106.1	108.2	78.0	1501.9	1833	27.5
Grapes	23.3	17.9	3.6	64.9	198.8	225.5	213.3	198.0	201.5	95.1	45.8	25.9	1313.6	41	0.5
Total	420.1	388.6	522.7	877.4	1582.5	1663.7	1436.0	1072.1	979.4	396.0	419.5	377.1	10135.1	9450	147.1

(d) S4 scenario (changed temperature and changed rainfall in 2050).

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	35.4	95.9	185.0	208.0	120.6	-	-	-	-	-	-	-	644.9	763	4.9
Barley	154.2	74.3	-	-	-	-	-	-	-	-	71.2	141.5	441.2	33	0.1
Tomato	-	-	-	4.4	150.3	223.6	288.4	271.5	167.6	-	-	-	1105.8	540	6.0
Potato	-	2.9	49.8	172.8	296.8	279.4	47.9	-	-	-	-	-	849.6	32	0.3
Other vegetables	-	-	-	5.1	183.5	266.1	262.9	15.0	-	-	-	-	732.6	927	6.8
Clover	40.6	35.7	92.7	169.1	245.1	257.5	244.1	229.5	234.1	61.8	65.3	42.0	1717.5	1914	32.9
Dates	113.2	111.7	145.6	175.3	252.6	265.2	251.5	238.2	250.3	146.4	147.1	110.1	2207.2	3367	74.3
Citrus	85.0	81.3	89.2	122.7	188.4	198.4	175.3	163.3	169.7	113.1	115.2	83.6	1585.2	1833	29.1
Grapes	26.0	20.6	5.8	69.5	206.3	233.5	221.4	207.7	212.8	101.2	49.0	28.4	1382.2	41	0.6
Total	454.4	422.4	568.1	926.9	1643.6	1723.7	1491.5	1125.2	1034.5	422.5	447.8	405.6	10666.2	9450	154.9

Table A.11: CWR for different crops under various scenarios in Al-Baha region

(a) S1 scenario (current temperature and rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	36.1	107.6	186.6	201.5	98.4	-	-	-	-	-	-	-	630.2	413	2.6
Millet (Grains)	38.6	130.0	156.1	44.4	-	-	-	-	-	-	-	-	369.1	3	0.01
sorghum	-	-	-	2.1	65.7	177.3	234.3	177.6	3.9	-	-	-	660.9	76	0.5
Maize	-	-	-	18.3	151.6	256.4	244.3	44.5	-	-	-	-	715.1	99	0.7
Barley	148.1	90.9	-	-	-	-	-	-	-	-	64.8	130.2	434.0	60	0.3
Tomato	-	-	-	-	68.5	140.6	238.4	261.5	225.1	33.5	-	-	967.6	108	1.0
Potato	-	2.7	59.0	162.8	244.2	220.3	41.2	-	-	-	-	-	730.2	6	0.04
Other vegetables	-	-	-	4.9	148.3	210.7	240.5	14.6	-	-	-	-	619.0	251	1.6
Clover	44.8	51.2	97.8	158.3	198.9	203.0	222.8	219.9	203.5	74.0	56.2	40.1	1570.5	52	0.8
Dates	117.7	135.7	153.2	168.6	209.8	213.1	228.4	205.3	195.4	170.1	126.6	97.5	2021.4	1395	28.2
Citrus	82.5	101.2	105.4	117.3	141.7	147.1	161.5	157.5	150.9	130.6	97.7	73.2	1466.6	43	0.6
Grapes	32.6	37.4	54.1	126.0	177.0	181.7	199.5	192.3	132.9	54.8	42.1	28.8	1259.2	194	2.4
Total	500.4	656.7	812.2	1004.2	1504.1	1750.2	1810.9	1273.2	911.7	463.0	387.4	369.8	11443.8	2700	38.8

(b) S2 scenario (changed temperature in 2050 and current rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	38.5	113.8	198.3	213	102.9	-	-	-	-	-	-	-	666.5	413	2.8
Millet (Grains)	41.2	137.3	166.2	48.0	-	-	-	-	-	-	-	-	392.7	3	0.01
sorghum	-	-	-	2.2	68.9	184.7	246.1	186.9	4.1	-	-	-	692.9	76	0.5
Maize	-	-	-	20.4	158.1	267.0	256.6	46.9	-	-	-	-	749.0	99	0.7
Barley	148.1	90.9	-	-	-	-	-	-	-	-	64.8	130.2	434.0	60	0.3
Tomato	-	-	-	-	71.5	146.8	250.7	275.6	239.2	36.0	-	-	1019.8	108	1.1
Potato	-	2.8	64.4	172.5	254.6	229.6	43.1	-	-	-	-	-	767.0	6	0.05
Other vegetables	0.0	0.0	0.0	5.1	155.0	219.7	252.8	15.4	0.0	0.0	0.0	0.0	648.0	251	1.6
Clover	47.9	54.4	105.0	167.6	207.3	211.5	234.1	231.7	216.3	80.0	60.5	43.4	1659.7	52	0.9
Dates	125.1	143.1	162.8	178.1	218.4	221.7	239.5	216.9	208.1	183.7	136.2	104.9	2138.5	1395	29.8
Citrus	87.6	106.8	112.7	124.4	148.2	153.6	169.9	166.0	160.1	140.4	104.5	78.4	1552.6	43	0.7
Grapes	34.9	39.7	59.0	133.7	184.4	189.1	209.4	202.5	140.9	59.3	45.3	31.3	1329.5	194	2.6
Total	523.3	688.8	868.4	1065.0	1569.3	1823.7	1902.2	1341.9	968.7	499.4	411.3	388.2	12050.2	2700	41.0

Table A.11: Continued

(c) S3 scenario (changed rainfall in 2050 and current temperature)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	38.2	111.6	192.2	201.3	98.7	-	-	-	-	-	-	-	642.0	413	2.7
Millet (Grains)	41.9	134.0	161.7	44.4	-	-	-	-	-	-	-	-	382.0	3	0.01
sorghum	-	-	-	2.1	65.9	176.0	235.3	159.0	3.9	-	-	-	642.2	76	0.5
Maize	-	-	-	17.6	151.8	255.1	245.2	40.6	-	-	-	-	710.3	99	0.7
Barley	143.2	89.8	-	-	-	-	-	-	-	-	55.3	112.2	400.5	60	0.2
Tomato	-	-	-	-	68.6	139.3	239.3	242.9	183.4	25.2	-	-	898.7	108	1.0
Potato	-	2.7	64.6	162.5	244.4	219.0	41.4	-	-	-	-	-	734.6	6	0.04
Other vegetables	-	-	-	4.9	148.5	209.4	241.4	14.6	-	-	-	-	618.8	251	1.6
Clover	48.8	55.2	103.4	158.0	199.1	201.7	223.7	201.2	161.8	26.8	51.2	31.1	1462.0	52	0.8
Dates	121.7	139.7	158.7	168.4	210.0	211.7	229.3	186.7	153.7	122.9	121.7	88.5	1913.0	1395	26.7
Citrus	86.5	105.2	111.0	117.0	141.9	145.8	162.5	138.9	109.3	83.4	92.7	64.2	1358.4	43	0.6
Grapes	36.5	41.4	59.7	125.8	177.3	180.3	200.4	173.7	91.2	7.9	37.2	19.8	1151.2	194	2.2
Total	516.8	679.6	851.3	1002.0	1506.2	1738.3	1818.5	1157.6	703.3	266.2	358.1	315.8	10913.7	2700	36.9

(d) S4 scenario (changed temperature and changed rainfall in 2050).

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
wheat	40.5	117.8	203.9	212.9	103.1	-	-	-	-	-	-	-	678.2	413	2.8
Millet (Grains)	44.5	141.3	171.8	48.0	-	-	-	-	-	-	-	-	405.6	3	0.01
sorghum	-	-	-	2.2	69.1	183.4	247.0	168.3	4.1	-	-	-	674.1	76	0.5
Maize	-	-	-	19.8	158.3	265.7	257.5	43.0	-	-	-	-	744.3	99	0.7
Barley	152.1	94.9	-	-	-	-	-	-	-	-	59.8	121.2	428.0	60	0.3
Tomato	-	-	-	-	71.6	145.5	251.6	257.0	197.5	27.6	-	-	950.8	108	1.0
Potato	-	2.8	69.9	172.2	254.8	228.3	43.4	-	-	-	-	-	771.4	6	0.05
Other vegetables	-	-	-	5.1	155.2	218.3	253.7	15.4	-	-	-	-	647.7	251	1.6
Clover	51.9	58.3	110.5	167.3	207.5	210.2	235.0	213.1	174.6	32.8	55.5	34.4	1551.1	52	0.8
Dates	129.1	147.1	168.4	177.9	218.6	220.3	240.4	198.3	166.5	136.5	131.2	95.9	2030.2	1395	28.3
Citrus	91.6	110.8	118.2	124.1	148.4	152.3	170.8	147.4	118.4	93.2	99.6	69.5	1444.3	43	0.6
Grapes	38.9	43.7	64.5	133.4	184.7	187.8	210.3	183.9	99.2	12.1	40.4	22.3	1221.2	194	2.4
Total	548.6	716.7	907.2	1062.9	1571.3	1811.8	1909.7	1226.4	760.3	302.2	386.5	343.3	11546.9	2700	39.1

Table A.12: CWR for different crops under various scenarios in Al-Jouf region

(a) S1 scenario (current temperature and rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	25.8	92.5	211.5	266.1	134.9	-	-	-	-	-	-	-	730.8	65162	476.2
Maize	-	-	-	-	-	-	-	49.1	168.0	231.0	145.0	22.8	615.9	2179	13.4
Barley	104.0	72.7	-	-	-	-	-	-	-	-	50.3	84.6	311.6	801	2.5
Tomato	-	-	-	127.0	230.0	362.0	394.0	220.0	-	-	-	-	1333.0	693	9.2
Potato	23.1	77.1	205.0	267.0	197.0	-	-	-	-	-	-	-	769.2	1837	14.1
Other vegetables	-	-	124.0	223.0	291.0	28.9	-	-	-	-	-	-	666.9	1601	10.7
Clover	83.9	109.0	64.3	79.8	109.0	122.0	135.0	231.0	263.0	185.0	122.0	72.2	1576.2	11908	187.7
Dates	87.8	119.0	187.0	197.0	246.0	277.0	301.0	278.0	268.0	193.0	127.0	75.5	2356.3	5470	128.9
Citrus	63.8	86.1	119.0	150.0	192.0	216.0	235.0	214.0	188.0	129.0	87.0	54.8	1734.7	727	12.6
Grapes	61.9	82.7	102.0	56.4	82.0	91.1	100.0	92.0	124.0	130.0	91.6	53.2	1066.9	1628	17.4
Total	450.3	639.1	1012.8	1366.3	1481.9	1097.0	1165.0	1084.1	1011.0	868.0	622.9	363.1	11161.5	92006	872.7

(b) S2 scenario (changed temperature in 2050 and current rainfall)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	28.5	100.8	226.1	282.5	140.3	-	-	-	-	-	-	-	778.2	65162	507.1
Maize	-	-	-	-	-	-	-	52.2	178.0	248.0	158.0	25.3	661.5	2179	14.4
Barley	114.0	79.3	-	-	-	-	-	-	-	-	55.2	92.9	341.4	801	2.7
Tomato	-	-	-	135.0	239.0	379.0	414.0	233.0	-	-	-	-	1400.0	693	9.7
Potato	25.6	84.0	220.0	283.0	205.0	-	-	-	-	-	-	-	817.6	1837	15.0
Other vegetables	-	-	133.0	237.0	302.0	30.3	-	-	-	-	-	-	702.3	1601	11.2
Clover	92.1	118.0	69.2	85.4	114.0	128.0	142.0	245.0	279.0	199.0	133.0	79.4	1684.1	11908	200.5
Dates	96.1	129.0	200.0	209.0	256.0	291.0	317.0	295.0	285.0	208.0	138.0	82.8	2506.9	5470	137.1
Citrus	70.0	93.5	127.0	160.0	199.0	225.0	246.0	226.0	199.0	139.0	94.7	60.3	1839.5	727	13.4
Grapes	68.0	89.9	110.0	60.6	85.3	95.6	105.0	97.6	131.0	140.0	100.0	58.6	1141.6	1628	18.6
Total	494.3	694.5	1085.3	1452.5	1540.6	1148.9	1224.0	1148.8	1072.0	934.0	678.9	399.3	11873.1	92006	929.8

Table A.12: Continued

(c) S3 scenario (changed rainfall in 2050 and current temperature)

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	22.2	95.6	213.6	269.5	134.9	-	-	-	-	-	-	-	735.8	65162	479.5
Maize	-	-	-	-	-	-	-	47.5	161.0	229.0	146.0	23.2	606.7	2179	13.2
Barley	95.9	75.7	-	-	-	-	-	-	-	-	52.0	84.3	307.9	801	2.5
Tomato	-	-	-	130.0	230.0	362.0	394.0	218.0	-	-	-	-	1334.0	693	9.2
Potato	19.5	80.1	207.0	270.0	197.0	-	-	-	-	-	-	-	773.6	1837	14.2
Other vegetables	-	-	126.0	226.0	291.0	28.9	-	-	-	-	-	-	671.9	1601	10.8
Clover	76.3	112.0	66.4	83.3	109.0	122.0	135.0	229.0	256.0	183.0	123.0	71.9	1566.9	11908	186.6
Dates	80.2	122.0	189.0	200.0	246.0	277.0	301.0	276.0	261.0	191.0	128.0	75.2	2346.4	5470	128.3
Citrus	56.2	89.1	121.0	153.0	192.0	216.0	235.0	212.0	181.0	128.0	88.6	54.5	1726.4	727	12.6
Grapes	54.3	85.7	105.0	59.9	82.0	91.2	100.0	89.5	117.0	128.0	93.4	52.8	1058.8	1628	17.2
Total	404.6	660.2	1028.0	1391.7	1481.9	1097.1	1165.0	1072.0	976.0	859.0	631.0	361.9	11128.4	92006	874.1

(d) S4 scenario (changed temperature and changed rainfall in 2050).

Crop	Monthly CWR (mm)												Total CWR mm/yr	Area (ha)	Total CWR (MCM /yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Wheat	24.9	103.7	228.3	286.0	140.3	-	-	-	-	-	-	-	783.2	65162	510.3
Maize	-	-	-	-	-	-	-	50.5	171.0	247.0	159.0	25.8	653.3	2179	14.2
Barley	106.0	82.3	-	-	-	-	-	-	-	-	56.9	92.6	337.8	801	2.7
Tomato	-	-	-	138.0	239.0	379.0	414.0	231.0	-	-	-	-	1401.0	693	9.7
Potato	21.9	87.0	222.0	287.0	205.0	-	-	-	-	-	-	-	822.9	1837	15.1
Other vegetables	-	-	135.0	240.0	302.0	30.3	-	-	-	-	-	-	707.3	1601	11.3
Clover	84.4	121.0	71.4	88.9	114.0	128.0	142.0	243.0	272.0	198.0	134.0	79.0	1675.7	11908	199.5
Dates	88.5	132.0	202.0	213.0	256.0	291.0	317.0	292.0	278.0	206.0	140.0	82.5	2498.0	5470	136.6
Citrus	62.4	96.5	129.0	163.0	199.0	225.0	246.0	223.0	192.0	138.0	96.4	60.0	1830.3	727	13.3
Grapes	60.4	92.8	112.0	64.1	85.3	95.6	105.0	95.0	124.0	139.0	102.0	58.2	1133.4	1628	18.5
Total	448.5	715.3	1099.7	1480.0	1540.6	1148.9	1224.0	1134.5	1037.0	928.0	688.3	398.1	11842.9	92006	931.4

APPENDIX (B): Some CROPWAT Software Results

(1) Riyadh

Monthly ETo Penman-Monteith - C:\Program Files\CLIMWAT 2.0 for CROPWAT V2.0\My_CLIM...

Country: Location 5 — Station: RIYADH

Altitude: 612 m. — Latitude: 24.71 °N — Longitude: 46.71 °E

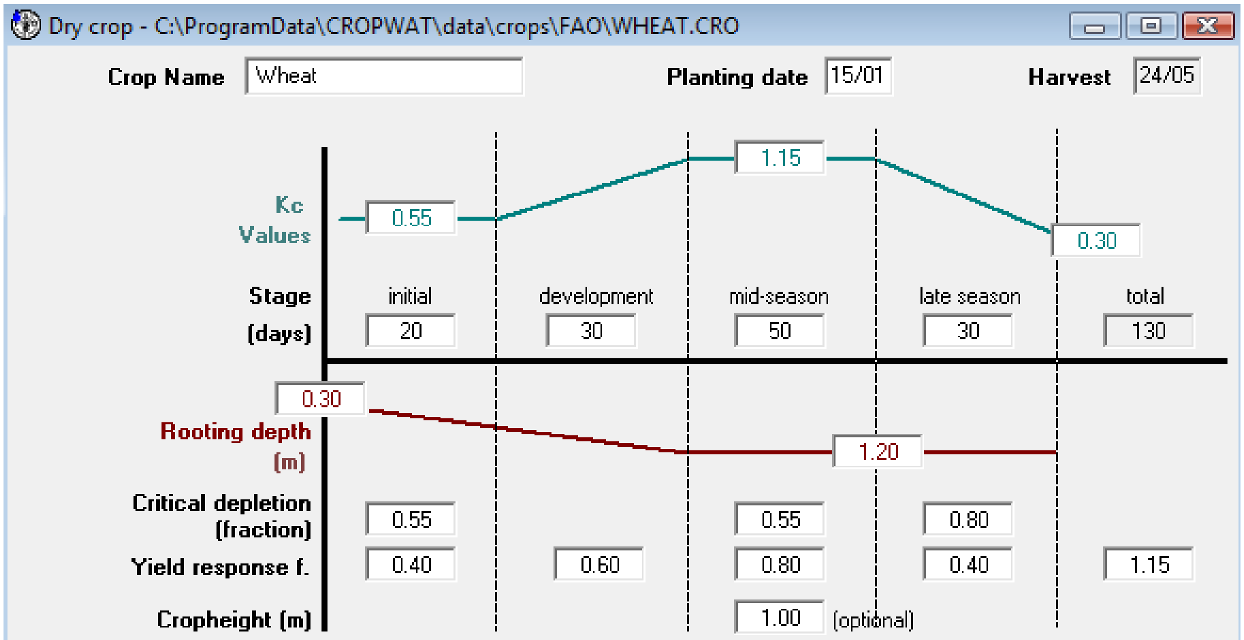
Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	8.2	20.2	51	245	6.7	13.8	3.30
February	10.3	22.9	48	245	7.4	16.5	4.00
March	14.4	27.6	37	245	7.1	18.3	5.38
April	18.9	32.3	33	334	7.4	20.4	7.53
May	24.2	38.7	22	289	7.8	21.7	8.96
June	26.2	41.5	15	334	9.6	24.4	10.93
July	27.4	42.8	16	311	9.4	24.0	10.70
August	27.0	42.5	16	267	9.3	23.4	9.73
September	24.1	40.1	17	245	8.6	20.9	8.49
October	19.2	34.6	22	200	8.1	18.0	6.29
November	14.3	27.4	44	156	7.4	14.9	3.88
December	9.4	21.7	44	178	6.3	12.7	3.20
Average	**18.6**	**32.7**	**30**	**254**	**7.9**	**19.1**	**6.86**

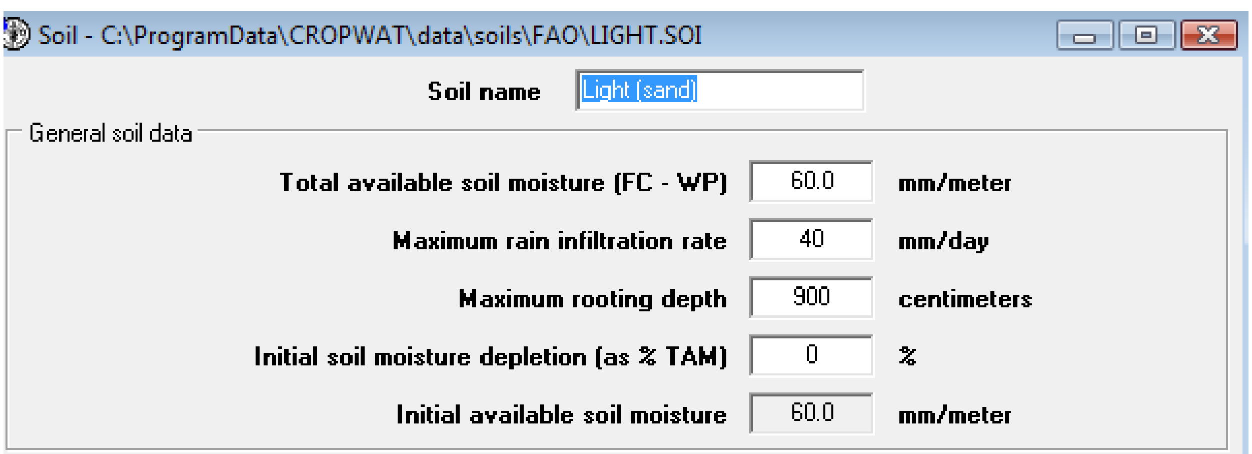
Monthly rain - C:\Program Files\CLIMWAT 2.0 for CROPWAT V2.0\My_CLIMWAT_File...

Station: RIYADH — Eff. rain method: USDA S.C. Method

	Rain	Eff rain
	mm	mm
January	11.3	11.1
February	10.1	9.9
March	24.0	23.1
April	29.4	28.0
May	7.8	7.7
June	0.1	0.1
July	0.4	0.4
August	0.6	0.6
September	0.1	0.1
October	1.2	1.2
November	5.6	5.5
December	10.7	10.5
Total	**101.3**	**98.3**

Riyadh: Continued





Riyadh: Continued

Crop Water Requirements

ETo station: RIYADH | Crop: Wheat

Rain station: RIYADH | Planting date: 15/01

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jan	2	Init	0.55	1.81	10.9	2.2	9.0
Jan	3	Init	0.55	1.94	21.4	3.6	17.8
Feb	1	Deve	0.61	2.29	22.9	3.0	19.9
Feb	2	Deve	0.82	3.26	32.6	2.7	29.9
Feb	3	Deve	1.01	4.49	35.9	4.3	31.6
Mar	1	Mid	1.17	5.74	57.4	6.5	50.9
Mar	2	Mid	1.19	6.39	63.9	8.0	55.9
Mar	3	Mid	1.19	7.25	79.7	8.5	71.2
Apr	1	Mid	1.19	8.10	81.0	9.6	71.4
Apr	2	Mid	1.19	8.95	89.5	10.5	79.1
Apr	3	Late	1.13	9.02	90.2	7.8	82.4
May	1	Late	0.85	7.20	72.0	4.5	67.5
May	2	Late	0.55	4.94	49.4	2.0	47.4
May	3	Late	0.34	3.31	13.2	0.5	12.6
					720.1	**73.7**	**646.6**

(2) Madinah

Monthly ETo Penman-Monteith - C:\Program Files\CLIMWAT 2.0 for CROPWAT V2.0\My_CLIM...

Country: Location 7 | Station: MADINAH

Altitude: 636 m. | Latitude: 24.55 °N | Longitude: 39.70 °E

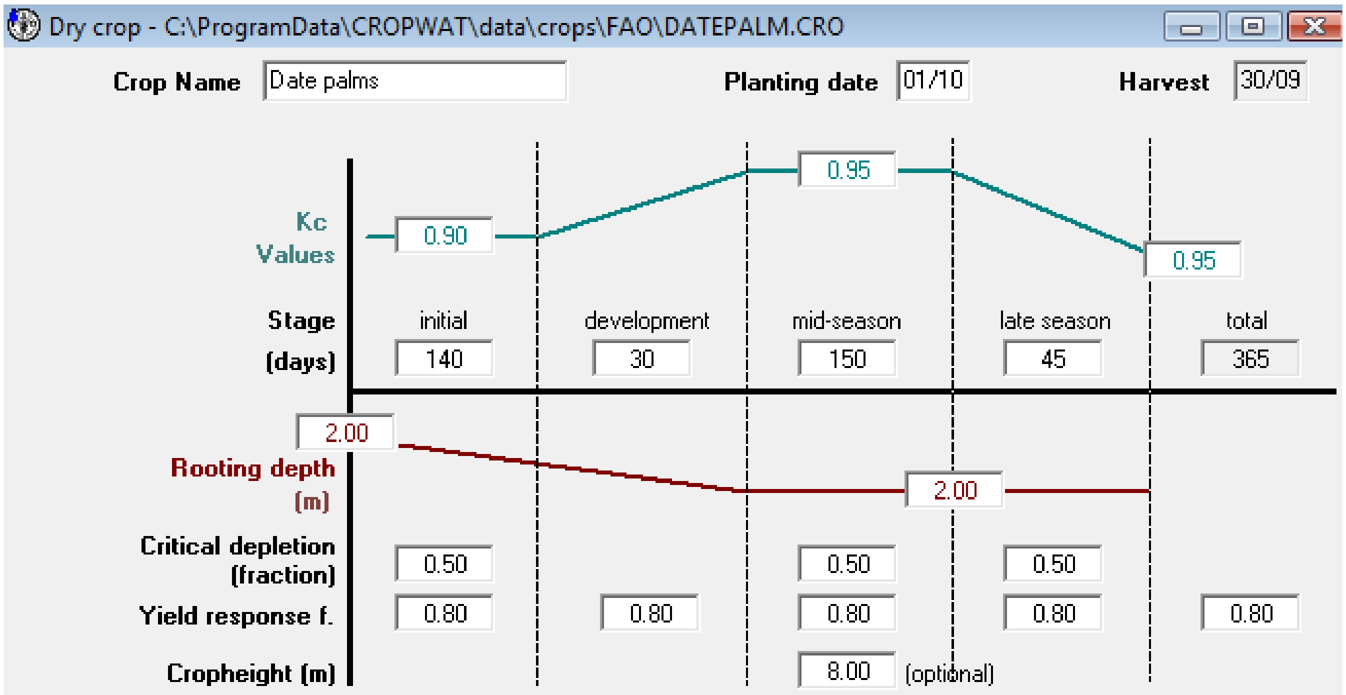
Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	11.6	23.6	43	178	6.8	13.9	3.44
February	13.3	26.1	43	222	7.9	17.2	4.45
March	17.4	30.2	27	267	6.7	17.8	6.36
April	20.8	33.9	25	311	6.9	19.7	7.97
May	24.9	38.9	19	267	8.3	22.4	8.87
June	27.9	41.7	14	222	10.3	25.5	9.12
July	28.4	39.3	17	267	10.2	25.2	9.59
August	28.7	42.2	19	222	10.0	24.4	8.87
September	27.1	41.0	18	178	8.5	20.8	7.35
October	21.9	36.4	23	178	8.3	18.3	6.17
November	17.2	29.7	41	222	8.0	15.7	4.91
December	12.9	25.0	42	178	5.4	11.7	3.50
Average	**21.0**	**34.0**	**28**	**226**	**8.1**	**19.4**	**6.72**

Monthly rain - C:\Program Files\CLIMWAT 2.0 for CROPWAT V2.0\My_CLIMWAT_File...

Station: MADINAH | Eff. rain method: USDA S.C. Method

	Rain	Eff rain
	mm	mm
January	8.0	7.9
February	1.2	1.2
March	8.3	8.2
April	11.9	11.7
May	4.6	4.6
June	0.4	0.4
July	0.2	0.2
August	0.3	0.3
September	0.1	0.1
October	1.1	1.1
November	9.2	9.1
December	3.8	3.8
Total	**49.1**	**48.5**

Madinah: Continued



Madinah: Continued

Crop Water Requirements

ETo station: MADINAH — Crop: Date palms

Rain station: MADINAH — Planting date: 01/10

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Oct	1	Init	0.90	5.91	59.1	0.1	59.0
Oct	2	Init	0.90	5.56	55.6	0.1	55.5
Oct	3	Init	0.90	5.18	57.0	1.1	55.9
Nov	1	Init	0.90	4.80	48.0	2.5	45.5
Nov	2	Init	0.90	4.42	44.2	3.6	40.6
Nov	3	Init	0.90	4.00	40.0	2.8	37.1
Dec	1	Init	0.90	3.51	35.1	1.6	33.5
Dec	2	Init	0.90	3.06	30.6	0.9	29.7
Dec	3	Init	0.90	3.07	33.8	1.5	32.3
Jan	1	Init	0.90	3.06	30.6	2.5	28.0
Jan	2	Init	0.90	3.01	30.1	3.1	27.0
Jan	3	Init	0.90	3.34	36.8	2.2	34.5
Feb	1	Init	0.90	3.70	37.0	0.6	36.4
Feb	2	Deve	0.90	4.02	40.2	0.0	40.2
Feb	3	Deve	0.92	4.69	37.5	0.7	36.9
Mar	1	Deve	0.95	5.43	54.3	2.1	52.3
Mar	2	Mid	0.98	6.22	62.2	2.9	59.3
Mar	3	Mid	0.99	6.82	75.0	3.2	71.8
Apr	1	Mid	0.99	7.35	73.5	3.8	69.7
Apr	2	Mid	0.99	7.88	78.8	4.3	74.5
Apr	3	Mid	0.99	8.18	81.8	3.4	78.4
May	1	Mid	0.99	8.48	84.8	2.2	82.6
May	2	Mid	0.99	8.78	87.8	1.4	86.4
May	3	Mid	0.99	8.86	97.5	1.0	96.5
Jun	1	Mid	0.99	8.94	89.4	0.5	89.0
Jun	2	Mid	0.99	9.03	90.3	0.0	90.3
Jun	3	Mid	0.99	9.18	91.8	0.0	91.7
Jul	1	Mid	0.99	9.40	94.0	0.1	93.9
Jul	2	Mid	0.99	9.58	95.8	0.1	95.8
Jul	3	Mid	0.99	9.31	102.4	0.1	102.4
Aug	1	Mid	0.99	9.01	90.1	0.1	90.0
Aug	2	Late	0.99	8.77	87.7	0.1	87.6
Aug	3	Late	0.98	8.21	90.3	0.1	90.2
Sep	1	Late	0.97	7.64	76.4	0.1	76.4
Sep	2	Late	0.97	7.09	70.9	0.0	70.9
Sep	3	Late	0.96	6.66	66.6	0.1	66.5
					2357.0	**48.8**	**2308.2**

REFERENCES

[1]. Mimi, Z.A. and Jamous, S.A., "Climate change and agricultural water demand: Impacts and adaptations." African Journal of Environmental Science and Technology 4(4): 183-191, 2010.

[2]. Jones, P.D. and Briffa, K.R., "Global surface air temperature variations during the twentieth century: Part I. Spatial, temporal and seasonal details." The Holocene 2(2): 165-179, 1992.

[3]. Bates, B.C., Kundzewicz, S.W and Palutikof, E. ds., "Climate Change and Water." Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, PP 210, 2008.

[4]. Chowdhury, S., Al-Zahrani, M., "Implications of climate change on water resources in Saudi Arabia." The Arabian Journal for Science and Engineering (AJSE). In press, 2012.

[5]. AEA Energy and Environment, "Adaptation to climate change in the agricultural sector." Report to European Commission Directorate- General for Agriculture and Rural Development AGRI -G4-05, 2007.

[6]. Saudi Geological Survey (SGS), "Facts and Figures." First published in Saudi Arabia, 2012.

[7]. Chowdhury, S., Al-Zahrani, M., "Characterizing water resources and trends of sector wise water consumptions in Saudi Arabia." Journal of King Saud University – Engineering Sciences, 2013 http://dx.doi.org/10.1016/j.jksues.2013.02.002

[8]. Al-Zawad, F.M., "Impacts of Climate Change on Water Resources in Saudi Arabia." The 3rd International Conference on Water Resources and Arid Environments and the 1st Arab Water Forum. Riyadh (Saudi Arabia) 16-19 November 2008.

[9]. FAO, "CLIMWAT: A climatic database for irrigation planning and management." FAO, 2000 Available at: http://www.fao.org/nr/water/infores_databases.html (accessed on Sep 10, 2012).

[10]. Saudi Statistical year book (SSYB), "Statistical year book – 2010." Ministry of Economy and Planning. Central Department of Statistics and Information, 2010.

[11]. Ministry of Agriculture (MOA), "Agriculture Statistical year book." Saudi Arabia, 2009. Available at: http://www.moa.gov.sa/public/portal (Accessed on Oct 20, 2012).

[12]. Ministry of Agriculture and Water (MAW), "Water Atlas of Saudi Arabia." Riyadh, Saudi Arabia, 1984.

[13]. Ministry of Agriculture and Water (MAW), "Atlas of land resources of Saudi Arabia." Riyadh, Saudi Arabia, 1994.

[14]. Abderrahman, W.A., "Water demand management in Saudi Arabia." In: Farukui N.I., Biswas 499 A.K. and Bino M.J. (eds.). Water Management in Islam, the International Development 500 Research Centre (IDRC), 68-78, 2001.

[15]. Alkolibi, F.M., "Possible Effects of Global Warming on Agriculture and Water Resources in Saudi Arabia: Impacts and Responses." Climatic change 54: 225-245, 2002.

[16]. IPCC, "General guidelines on the use of scenario data for climate impact and adaptation assessment." Cambridge and New York: Cambridge University Press, 2007.

[17]. Gohari, A., Eslamian, S., Abedi-Koupaei, J., Massah Bavani, A., Wang, D., and Madani, K., "Climate change impacts on crop production in Iran's Zayandeh-Rud River Basin." Science of the Total Environment 442: 405–419, 2013

[18]. IPCC (Intergovernmental Panel on Climate Change), "First assessment report." In: Houghton, J.T., Jenkins, G.J., Ephraums, J.J. (Eds.), Scientific Assessment of Climate Change — Report of Working Group I. Cambridge University Press, UK., 1990.

[19]. IPCC (Intergovernmental Panel on Climate Change), "Second assessment report of climate change." In: Houghton, J.T., Meira Filho, L.G., Callender, B.A., Harris, N., Kattenburg, A., Maskell, K. (Eds.), The Science of Climate Change. Cambridge University Press, UK, 1995.

[20]. Southworth, J., Randolph, J. C., Habeck, M., Doering, O. C., Pfeifer, R. a., Rao, D. G., and Johnston, J. J., "Consequences of future climate change and changing climate variability on maize yields in the mid-western United States." Agriculture, Ecosystems & Environment, 82(1-3):139–158, 2000.

[21]. IPCC, “Climate Change 2007: The Physical Science Basis.” Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.). Cambridge University Press, Cambridge, United Kingdom/New York, NY, USA, 2007 b.

[22]. Högy, P., Poll, C., Marhan, S., Kandeler, E., & Fangmeier, A., “Impacts of temperature increase and change in precipitation pattern on crop yield and yield quality of barley.” Food chemistry, 136(3-4):1470–7, 2013.

[23]. Reidsma, P., Ewert, F., Lansink, A. O., and Leemans, R., “Adaptation to climate change and climate variability in European agriculture: The importance of farm level responses.” European Journal of Agronomy, 32(1): 91–102, 2010.

[24]. Mestre-Sanchís, F., and Feijóo-Bello, M. L., “Climate change and its marginalizing effect on agriculture.” Ecological Economics, 68(3): 896–904, 2009.

[25]. Parry, M.L. and Swaminathan, M.S., “Effect of Climatic Change on Food Production.” In Mintzer, I. M. (ed.), Confronting Climatic Change: Risks, Implications, and Responses, Chapter 8, Cambridge University Press, 1993.

[26]. Parry, M.L., Rosenzweig, C., Iglesias, A., Fischer, G., Livermore, M., “Climate Change and World Food Security: A New Assessment.” Global Environ. Change 9, S51–S67, 1999.

[27]. MOEP (The Ministry of Economy and Planning), “The ninth development plan (2010 – 2014).” Saudi Arabia. Legal Deposit No. 16/0694 ISSN: 1319 – 4836, 2010.

[28]. FAO (Food and Agriculture Organization), “Proceedings of the Second Expert Consultation on National Water Policy Reform in the Near East.” Cairo, Egypt, 24–25 November 1997.

[29]. MOWE (Ministry of Water and Electricity), “Kingdom of Saudi Arabia: Dams.” Available at :< http://intranet.mowe.gov.sa/Dams/>, 2011.

[30]. MOWE (Ministry of Water and Electricity), “The Ministry of Water and Electricity Annual report.” Riyadh, Saudi Arabia, 2009.

[31]. Al-Saleh, M. A., “Declining ground water level of the Minjure aquifer, Tebrak area.” Saudi Arabia. The Geographical Journal 158(2): 215-222, 1992.

[32]. Mustafa, M. A., Akabawi, K. A. and Zoghet, M. F., "Irrigation water requirements of wheat in the life zones of Saudi Arabia." J. Arid Environ 17: 349-354, (1989).

[33]. Al-Omran, A. M. and Shalaby, A. A., "Calculation of water requirements for some crops in the eastern and central regions of the Kingdom of Saudi Arabia." J. coll. Agric. King Saud Univ 4: 97-114 (1992).

[34]. Al-Taher, A. A., "Crops irrigation scheduling." Arts College. King Saudi University, Riyadh. Saudi Arabia, 44pp, (1992b).

[35]. Al-Taher, A. A., "Effect of planting date on the consumptive use of wheat in Najd region, Saudi Arabia." Research Papers in Geography, the Saudi Geographical Society. Riyadh. Saudi Arabia, 47pp, (1993).

[36]. Al-Taher, A. A., "Quality and efficiency of irrigation water and its effect on the agricultural land in Yabrin Oasis, Saudi Arabia." Research Papers in Geography, the Saudi Geographical Society. Riyadh. Saudi Arabia, 53pp, (1994).

[37]. Saif ud din, Al-Rumikhani, Y. A., Latif, M. S., "Use of remote sensing and agrometeorology for irrigation management in arid lands: a case study from northwestern Saudi Arabia." Journal of Environmental Hydrology 12(9), (2004).

[38]. Almisnid A., "climate change and water use for irrigation: a case study in the Gassim area of saudi Arabia." A thesis submitted to the School of Development Studies at the University of East Anglia in fulfilment of the requirements for the degree of Ph.D., (2005).

[39]. Hashim M.A.A., Siam, N., Al-Dosari, A., Asl-Gaadi, K.A., Patil, V.C., Tola, E.H.M, Rangaswamy, M. and Samdani, M.S., "Determination of Water Requirement and Crop water productivity of Crops Grown in the Makkah Region of Saudi Arabia." Australian Journal of Basic and Applied Sciences, 6(9): 196-206, 2012.

[40]. Alamoud, A. I., Mohammad, F. S., Al-Hamed, S. A. and Alabdulkader. A. M., "Reference evapotranspiration and date palm water use in the kingdom of Saudi Arabia.", International Research Journal of Agricultural Science and Soil Science (ISSN: 2251-0044) Vol. 2(4) pp. 1 55-169, April 2012.

[41]. Supit, I., Van Diepen, C. a., De Wit, a. J. W., Wolf, J., Kabat, P., Baruth, B., and Ludwig, F., "Assessing climate change effects on European crop yields using the

Crop Growth Monitoring System and a weather generator." Agricultural and Forest Meteorology, 164: 96–111, 2012.

[42]. Schilling, J., Freier, K. P., Hertig, E., and Scheffran, J., "Climate change, vulnerability and adaptation in North Africa with focus on Morocco." Agriculture, Ecosystems & Environment, 156: 12–26, 2012.

[43]. Paeth, H., Born, K., Girmes, R., Podzun, R., and Jacob, J., "Regional climate change in Tropical and Northern Africa due to greenhouse forcing and land use changes." Journal of Climate 22:114–132, 2009.

[44]. Özdoğan, M., "Modeling the impacts of climate change on wheat yields in Northwestern Turkey." Agriculture, Ecosystems & Environment, 141(1-2), 1–12, 2011.

[45]. Connor, J. D., Schwabe, K., King, D., and Knapp, K., "Irrigated agriculture and climate change: The influence of water supply variability and salinity on adaptation." Ecological Economics, 77:149–157, 2012.

[46]. Fischer, G., Tubiello, F. N., Van Velthuizen, H., and Wiberg, D., "Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080." Technological Forecasting and Social Change, 74(7): 1083–1107, 2007.

[47]. Döll, P., "Impact of climate change and variability on irrigation requirements: a global perspective." Climatic Change 54: 269–293, 2002.

[48]. Mall, R. K., Gupta, A., Singh, R., Singh, R. S., and Rathore, L. S., "Water resources and climate change ." An Indian perspective, 90(12): 1610-1626, 2006.

[49]. Ghazala, N., and A. Mahmood, "Water requirement for Wheat Crop in Pakistan." Pakistan Journal of Meteorology 6(11): 89-96, 2009.

[50]. Allen, R. G., Pereira, L. S., Raes, D., Smith, M., "Crop evapotranspiration: Guidelines for computing crop water requirements - FAO Irrigation and Drainage Paper No. 56." Food and Agricultural Organization of the United Nations, Rome, Italy 300 pp., 1998.

[51]. FAO, "CROPWAT: A computer program for irrigation planning and management." Irrigation and Drainage Paper No. 46. Rome, 1992.

[52]. Alsadon, A.A., "The best planting dates for vegetables crops in Saudi Arabia: Evaluation of compatibility between the dates planned based on Heat Units and dates

suggested from the regional offices of the Ministry." Agricultural Sciences, 14 (1): 75 – 79, 2002.

[53]. Technical and Vocational Training Corporation (TVTC), "Vegetables production, Fodder crops and pastures, Production of field crops." Saudi Arabia, 2004.

[54]. Elnesr, M.N., Alazba, A.A. and Alsadon, A.A., "An arithmetic method to determine the most suitable planting dates for vegetables." Computer and Electronics in Agriculture 90: 131-143 (2013).

[55]. Al Jouf Agricultural Development Company, Al-Jouf, Saudi Arbia, Available at: http://www.aljouf.com.sa/en_default.aspx, (accessed on Jan, 2013).

[56]. Kader, A.A. and Hussein, Awad, "Harvesting and postharvest handling of dates." ICARDA, Aleppo, Syria. iv + 15 pp., (2009).

[57]. AL-Saif, A. M., "Evaluation and Selection of Some Local Grape Cultivars Grown in Riyadh Region.", Saudi Arabia, Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science (Horticulture – Pomology) Department of Plant Production, College of Agriculture, King Saud University, Riyadh, 1999.

[58]. Smith, M. and Kivumbi, D., "Calculation procedure Use of the FAO CROPWAT model in deficit irrigation studies." FAO (Food and Agriculture Organization), Rome, Italy; Heng, L. K., Joint FAO/IAEA Division, International Atomic Energy Agency, Vienna, Austria, 2006.

[59]. George, B., Shende, S. and Raghuwanshi, N., "Development and testing of an irrigation scheduling model." Agricultural Water Management, 46(2):121-136, 2000.

[60]. Anadranistakis, M., Liakatas, A., Kerkides, P. and Rizos, S., "Crop water requirements model tested for crop grown in Greece." Agricultural Water Management, 45(3): 297-316, 2000.

[61]. Sheng-Feng, K., Yi-Wen, C. and Sheng-Hsien, S., "Study on Soil and Water Resource Management for ChiaNan Irrigation Association in Taiwan." College of management, Taiwan. PP 90-109, 2001.

[62]. Wahaj, R., Marauxet, F. and Munoz, G., "Actual crop water use in project countries: a synthesis at the regional level." The GEF funded project: Climate Change Impacts on and Adaptation of Agro ecological Systems in Africa, PP 1-50, 2003.

[63]. Kang, S., Payne, W.A., Evett, S.R., Stewart, B.A. and Robinson, C.A., "Simulation of winter wheat evapotranspiration in Texas and Henan using three models of differing complexity." Agricultural Water Management 96: 167 – 178, 2009.

[64]. Nazeer, M., "Simulation of maize crop under irrigated and rainfed conditions with CROPWAT model." ARPN Journal of Agricultural and Biological Science. 4(2): 68-73, 2009.

[65]. Mimi, Z.A. and Jamous, S.A., "Climate change and agricultural water demand: Impacts and adaptations." African Journal of Environmental Science and Technology 4(4): 183-191, 2010.

[66]. Stancalie, G., Marica, A. and Toulios, L., "Using earth observation data and CROPWAT model to estimate the actual crop evapotranspiration." Physics and Chemistry of the Earth 35: 25–30, 2010.

[67]. Mhashu, S.V., "Yield response to water function and simulation of deficit irrigation scheduling of sugarcane at estate in Zimbabwe using CROPWAT 8.0 and CLIMWAT 2.0." Master thesis, Università degli Studi di Firenze Facoltá di Agraria (University of Florence, Faculty of Agriculture), 2007.

[68]. Molua, E.L. and Lambi, C.M., "Assessing the impact of climate on crop water use and crop water productivity." The CROPWAT Analysis of Three Districts in Cameroon, PP 1-44, 2006.

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